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**K-DIVISION EXPERIMENTAL WORK
PART I: GEOPHYSICS RESEARCH FOR
UNDERGROUND EXPLOSION TECHNOLOGY**

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PART I: GEOPHYSICS RESEARCH FOR

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Abstract

This report is a detailed discussion of all the research carried out by the Geophysics Research Group during the past four years. It updates material that has already been published elsewhere. Descriptions are given of tests of a dry hole acoustic log, a shear-wave downhole survey, and comparisons between commer-

cial logging systems and other logging methods. Computer programs for reducing logging data to physical properties are also discussed, as are programs for correlation and storage of logs. A proposed new method for measuring shear strength in place is also discussed.

A Word on Notation

This report was compiled from many other reports that have been written by the authors over the last four years, and it also

contains material written especially for this publication. Notation, therefore, is not entirely consistent throughout this report.

The Problem

Well logging, or geophysical logging is the investigation of the properties of earth materials using equipment lowered into holes in the ground. Holes several kilometers deep are routinely logged by a number of organizations specializing in this work. An extensive literature exists, mainly related to oilfield logging.¹⁻³ The data obtained range in quality from highly accurate to qualitative, depending on the logging company, the parameter being measured, the con-

dition of the borehole, and the rock type. Generally, sedimentary rocks such as limestone, shale, sandstone, and dolomite are very familiar to the loggers and the data from these rocks are by far the best.

In the engineering use of underground nuclear explosives, it is often highly desirable to calculate the effects of an explosion before it is fired.⁴ Such calculations require fairly accurate values of such parameters as density, acoustic

velocity, and water content, and the shear strength and specific volume as functions of pressure for the rock in and below which the device is fired.

Most of our experiments have been done at the Nevada Test Site, where the medium is often volcanic rock (such as rhyolite or basalt) or desert alluvium. These rocks are unfamiliar to oilfield practice, and therefore the logging techniques are not calibrated properly for them.

In oilfield work, many formulas have been developed that interrelate various parameters and are used to calibrate logging tool data using information derived from cores. Generally, these relationships do not apply at NTS above the water table, although some correlations have been found below it.⁵ Furthermore, a core often cannot be obtained over long sections (~100 m) of NTS holes.

When core data are available, they are often not representative of the in-situ properties of the medium. Density values tend to be biased; since coring tends

to select unfractured pieces of rock, the density decrease due to fractures is lost. Friable inclusions can also be lost in coring. Velocities measured on core samples are often similarly biased. Our interest in geophysical work began when a compressional velocity value derived from core data at an experimental site was found to be twice as high as that measured in place and verified at shot time.⁶

Hole conditions at NTS are also different from usual oilfield conditions. The holes are often dry; not only will they not hold water, they sometimes will not hold sand. The holes are often much rougher and much larger (up to 3 or 4 m in diameter) than those commonly encountered in industry. In the oilfield one can often use information from a nearby hole to help interpret data from another. At NTS there are often no nearby holes; when there are, there is often little correlation from hole to hole—even at distances of less than 50 m.

The Approach

The basic requirements on the data are that absolute values as accurate as possible be obtained and that all the information required to characterize the material be obtained from the borehole in question. If outside information is available, all the better, but such information must not be necessary to the approach. The basic requirement on the equipment is that it work properly under the borehole conditions at the test site and that it work in any rock-like material. There is a limitation in that if LRL equipment is

used, the same personnel must both build and field it.

When possible, equipment available from the industry is used. (There is a logging contractor at NTS.) Often it is necessary to modify the industrial equipment, calibration procedure, or data-reduction technique. Our work in defining and sometimes performing these modifications often cannot be published, since information proprietary to the logger may be involved.

When it appears that equipment available from contractors will not perform

satisfactorily under the conditions we face, we must design, fabricate, and field appropriate test equipment ourselves. The logging industry could build equipment to do the job, but it has little incentive to do so because such equipment may not be useful elsewhere.

Furthermore, we have some simplifying advantages over the logging industry. The industry must usually build equipment that works rapidly, since a drill rig often stands idle while logging takes place. Therefore, most industrial logging tools are designed to operate while moving fairly rapidly in the hole. In our method of operation, the drill rig usually leaves before logging begins, so we can use log-

ging equipment that works only while it is stationary. Also, LRL has a very large computation facility which, coupled with the fact that the data are not needed immediately after logging, permits much simpler field data-taking, with subsequent computer reduction. Finally, since the people who design and build the equipment also operate it, it need be neither as reliable nor as simple to operate as equipment designed for routine use by logging company personnel.

By taking advantage of these simplifications, we have been able to field a few instruments which, under existing conditions, perform much better than standard instruments.

Density

GRAVIMETRY

Two methods are used for measuring density in place. One, borehole gravimetry, has now become a commonly accepted, if not commonly used, practice.⁷⁻¹⁰ The expression for density as a function of gravity difference at two depths is given in a general form by McCulloh⁸ as

$$\rho = \frac{F + \frac{\Delta C_g}{\Delta z} - \frac{\Delta g_u}{\Delta z}}{4\pi k} \quad (1)$$

and

$$\Delta g_u = \Delta g_0 - \Delta C_t - \Delta C_b, \quad (2)$$

where ρ is the density, F is the free air gradient, Δg_0 is the measured gravity difference between two depths, Δz is the depth difference, ΔC_g is a correction for the effect of subsurface density differences (according to McCulloh, generally negligible), ΔC_t is the terrain correction,

ΔC_b is a borehole correction, and k is the gravitational constant. This equation can be obtained from first principles using Gauss's law.

Three simple computer programs have been written to investigate the effect of density anomalies on density measured by gravimetry. They tend to confirm that these effects are generally negligible. In all of these calculations, density contrast is used. It is defined as the difference between the density of the anomaly and that of the rest of the medium. In all problems to be discussed, the contrast is 2.5, corresponding to a void in a medium of density 2.5 g/cm³. (Density contrast is a multiplicative factor in the effect; thus, a contrast of 0.25 would have 10% of the effect of one of 2.5.)

The first code, G1.01N, calculates the effect of a spherical anomaly. For a

gravity measurement interval of 50 ft, a void 100 ft in radius, with its center in that interval and 200 ft from the borehole, would cause a density anomaly of 0.1 g/cm^3 . If the center of the sphere were 250 ft below the measured interval, its effect would be less than 0.1 g/cm^3 at any horizontal distance. A spherical void with a 50-ft radius has no effect as great as 0.1 g/cm^3 if it intersects neither the measured interval nor the borehole. It appears, then, that spherical voids are not significant, since if they are not close enough to be part of the measured interval, their effect is not measurable.

A second code, BOMBUR, is similar to GLÓIN, but it was written to see if spherical voids could be detected by gravimetry. It showed that a 100-ft-radius void tangent to the borehole would cause a maximum change of gravity of 0.1 mgal. This is quite discouraging for detecting holes some distance from the borehole.

A third code, ÓIN, investigated the effect of slab anomalies. Only calculations for 100 ft measurement intervals are available at present. Calculations were made for various angles of tilt of the slab and various slab thicknesses. Since the depth of the measurement also participates in the effect (because more of the slab is above a deeper measurement), it was also included. For a void 100 ft thick, there is never a change of measured density greater than 0.25 g/cm^3 unless the measurement takes place in the slab (where, of course, the change is real!). Changes in density greater than 0.1 g/cm^3 only take place when the 100-ft slab is 100 to 200 ft above the measured interval and fairly horizontal. Again, however, note that this effect is for a void. For reasonable

density contrasts, the effect of a slab anomaly that is not in the measured interval is therefore negligible.

All borehole gravimetry users have performed calculated terrain corrections, but the method has only been reported in one case¹¹ and it is cumbersome. Terrain correction methods for surface and airborne gravity measurements have been published,¹²⁻¹⁴ but they are not directly applicable to the borehole case.

We have written a computer program, MORIA, for the application of terrain corrections to borehole gravimetry measurements.

Equation (1) may conveniently be put in a difference form for the computer. Then we find that

$$\rho_n = \frac{F}{4\pi k} - \frac{(g_{n+1} - g_n) - (C_{n+1} - C_n)}{(d_{n+1} - d_n) 4\pi k}, \quad (3)$$

where the free air gradient F may be measured or taken from the literature (McCulloh suggests measurement, remembering to correct the measurement for terrain), C is the sum of all corrections, and d is the depth of the measurement ($d_{n+1} > d_n$). With this sign convention, the sign of the terrain correction will normally be negative for a surface measurement.

Heiskanen and Vening Meinesz¹⁵ derive the expression

$$\Delta g_c = 2\pi k \rho \left[\sqrt{r_1^2 + h^2} - \sqrt{r_1^2 + h_1^2} - \sqrt{r_2^2 + h^2} + \sqrt{r_2^2 + h_1^2} \right] \quad (4)$$

for the vertical gravitational attraction at point P of a cylindrical ring of inner radius r_1 and outer radius r_2 , whose base is a distance h from P , whose height is $h - h_1$, and whose axis passes vertically

through P (see Fig. 1). If, using Hammer's method,¹² the world is divided into S of these cylindrical rings with fixed radii, and these cylinders are divided into m wedge-shaped compartments each, with m varying with r_1 , then

$$C_n = \sum_{s,m} C_{m,n} = \sum_{s=1,S} \sum_{m=1,M} \frac{\Delta g_c(s,m)_n}{m}, \quad (5)$$

where Δg_c is calculated for the full cylindrical ring for the elevations of each compartment. Currently a total of 69 compartments is used to a radius of 5000 m, but this may be increased for rugged terrain.

Effort is minimized by using the elevations of each compartment, and of the

top of the hole, as taken from a topographic map. Those elevations, however, are difficult to obtain in rugged terrain. The difference in elevation ΔE_m between compartment and hole top is then calculated for each compartment. For each depth station, n, three cases are possible:

Case 1: $\Delta E_m > 0$ (surrounding terrain above hole top)

$$h_1 = d_n, \quad h = d + \Delta E_m$$

$C_{m,n}$ is calculated from Eqs. (4) and (5) and set negative.

Case 2: $\Delta E_m < 0$ (surrounding terrain below top)

$$d_n > |\Delta E_m|$$

$$h_1 = d_n - |\Delta E_m|$$

$$h = d_n$$

$C_{m,n}$ is set positive, since a "valley" exists above point d_n .

Case 3: $\Delta E_m < 0$

$$d_n < |\Delta E_m|$$

The calculation is divided into two parts; for the "valley" above d_n and for that below:

$$h_1 = 0, \quad h = d_n$$

and C_1 is calculated from Eq. (4);

$$h_1 = 0, \quad h = |\Delta E_m| - d_n$$

C_2 is calculated and

$$C_{m,n} = C_1 - C_2$$

The borehole is treated as a compartment in which Case 3 obtains.

The corrections are then summed as in Eq. (5) and the density is computed from Eq. (3).

A fourth case, with $\Delta E_m > 0$ but $d_n > |\Delta E_m|$ is used for correction of free-air gradient. Then

$$h = d_n$$

and

$$h_1 = d_n - \Delta E_m$$

Fig. 1. Illustration of gravimetric terrain correction.

$C_{m,n}$ is calculated and summed and then used as a correction to the free-air gradient as measured by setting the gravimeter on a tower and using Eq. (3) with $\rho = \phi$.

The effort involved in this method is the acquisition of the average elevations in each compartment from topographic maps, and this is required for any terrain correction method. It would be possible to "read" the maps with a computer flying-spot scanner, but the effort involved in preparing suitable maps and programming would be much greater than that involved in hand-reading.

The problem of the effect of a constant thickness sheet, posed by Chinnery,¹⁴ exists but is trivial as long as the thickness of the sheet is much less than r_{max} . The program does not currently contain the capability for tidal and drift corrections, but they can readily be added if the volume of work makes it desirable.*

The gravimetric method has the advantage of measuring density over large volumes of material and has a large radial range from the hole. It does not show detail, but the large volumes are useful for the computer calculations that do not take small details into account. However, it is particularly slow and costly to use, and no gravimeter is available to us on a regular basis.

We have tested a gravimeter designed by the Esso Production Research Co. and fielded by the Century Geophysical Co., but it was not in working order when

tested. A meter owned by the U. S. Geological Survey has appeared to be more satisfactory, and has been used once at the Test Site (see below).

GAMMA-GAMMA LOGGING WITH THE RIDS

The method commonly used by the logging industry for measuring density in place is that of backscattered gamma rays. However, difficulty has been experienced in the use of the ordinary density logs in the rough, air-filled holes at the Nevada Test Site. Consequently, a gamma-gamma density system, designed specifically to work in rough, air-filled holes, but also usable in smooth holes, has been designed. It is known as the RIDS (rugosity-insensitive density system), a density logger whose readings are not affected by irregularities in the sidewall of the hole. A working prototype has been built at the Nevada Test Site and tested in the laboratory as well as in the field. It has performed satisfactorily under conditions in which other systems failed to give credible data. This section summarizes the theory, design, and testing of the prototype system.

Theory of Gamma-Gamma Density Measuring Systems

General

The original design of the RIDS assumed that, because of sidewall irregularities, the sonde would not be in contact with the borehole wall and that the distance along the beam path between source, detector, and the borehole wall would be measured. The expression for intensity in this case is the most general

*The U. S. Geological Survey is using a much-improved version of MORIA that appears to include such corrections.

Fig. 2. Idealization of a single-Compton-scattering density tool.

one for a sonde utilizing single Compton scattering (see Fig. 2):

$$I = K \rho_{sv} e^{-Q}, \quad (6)$$

where

$$Q = [(x_1 - a)\mu_{m1} + (x_2 - b)\mu_{m2}] \rho_m + [a\mu_{f1} + b\mu_{f2}] \rho_f.$$

K is a constant that depends on source strength, solid angle, Klein-Nishina cross section, etc.; ρ_m is the electron density in the medium; ρ_{sv} is the electron density in the scattering volume (generally considered the same); and ρ_f is the electron density in the borehole fluid. The terms x_1 , x_2 , a , and b are distances as shown in Fig. 2; μ_{m1} and μ_{m2} are the mean mass attenuation coefficients for incident and scattered gamma rays in the

medium, μ_{f1} and μ_{f2} are those for the fluid; I is the detected intensity of gamma radiation in the energy region acceptable for single scattering.

Equation (1), of course, is strictly applicable to only one path, with only one incident and detected energy; a detailed prediction of I requires integration over incident and scattered angles determined by the collimators and over cross sections and attenuation coefficients appropriate to the angles. Such an integration has been performed for the actual design of the sonde, and will be discussed below.

The expression in Eq. (6) is double valued. With $a = b = 0$, the maximum is at $\rho = 1/C$, where $C = x_1\mu_{m1} + x_2\mu_{m2}$; therefore, the sonde must be long enough

that $1/C$ is well below densities of interest, so that no ambiguous results occur.

In reality, double scattering is a significant factor in the detected data. This gives rise to a second term, similar to Eq. (6), but of the form

$$I' = K_2 \rho^2 e^{-R}, \quad (7)$$

where R is a term similar to Q , but with other distances that are not readily calculable. The value of R may, however, be determined experimentally (see below).

Single Scattering Systems

There is at least one other system in which a collimated source and detector are used, but without assurance that $a = b = 0$.¹⁶ The density-vs-intensity curve obeys Eq. (6), and one must investigate the situation in which $a \neq b \neq 0$. Consider an air-filled borehole, where $\rho_f = 0$, and let $A = a\mu_{m1}$, $B = b\mu_{m2}$, and $C = x_1\mu_{m1} + x_2\mu_{m2}$. Then

$$I = K\rho e^{-(C-A-B)\rho} \quad (8)$$

and

$$\frac{d\rho}{\rho} \approx -\frac{(A+B)}{C-(A+B)}. \quad (9)$$

For example, for a sonde with a ^{137}Cs source and a distance of 25 cm from source port to detector port, a 1-cm gap (at both ends) would give an 8% error. Therefore, this system is rather sensitive to gaps between the sonde and borehole wall.

Two-Detector Systems

Several two-detector sondes are in use.^{17,18} While details of the systems are not supplied, it is assumed that they work by simultaneous application of two collimated detectors and one source, and

thus by simultaneous solution of two equations of the form of Eq. (6). The sonde must presumably be parallel to the wall; therefore, $A = B_1 = B_2$, where B_i applies to a given detector. The system then obeys

$$I_R = \frac{I_1}{I_2} = \frac{K_1}{K_2} \exp[-(C_1 - C_2)\rho] \quad (10)$$

and

$$\frac{d\rho}{\rho} = \frac{1}{\rho(C_2 - C_1)} \frac{dI_R}{I_R} \approx \frac{1}{\rho(C_2 - C_1)} \times \left[\left(\frac{dI_1}{I_1} \right)^2 + \left(\frac{dI_2}{I_2} \right)^2 \right]^{1/2}. \quad (11)$$

For $C_2 - C_1 = 2.45$ (similar to C in the RIDS) and $\rho = 2.0$, if $dI_1/I_1 = dI_2/I_2$, then $d\rho/\rho = 0.28 (dI_1/I_1)$. On the other hand, one must consider departure from parallelism. If $dB = B_2 - B_1$,

$$\frac{d\rho}{\rho} \approx \frac{-dB}{(C_2 - C_1) - dB} \approx \tan \theta, \quad (12)$$

where θ is the angle by which the sonde deviates from parallelism at the point of measurement. For even a small wash-out, dB is often not small, and even if $C_2 - C_1$ were as large as 2.5, for example a 1-cm difference in wall distance would give a 4% error.

Diffusion Systems

A fairly common type of sonde, which may be referred to as a diffusion system, has an uncollimated detector and may or may not have a collimated source. The detector is usually a Geiger counter, which has no energy discrimination. Gamma rays can scatter many times between source and detector, and their behavior may be approximated by diffusion

theory. Tittman and Wahl¹⁹ discuss this system and, for a sonde whose parameters are not specified, quote an expression

$$I = C \left(1 + \frac{r\rho}{14}\right) e^{-r\rho/14}, \quad (13)$$

where r is the source detector distance. Then

$$\frac{d\rho}{\rho} = \frac{1 + r\rho/14}{r^2 \rho^2 / 196} \frac{dI}{I}, \quad (14)$$

and using their values of $r = 40$ cm and $\rho = 2.0$, $d\rho/\rho = 0.275 dI/I$. Gap effects cannot be calculated from this, but one company states that in a dry hole with a gap of 1 cm, $d\rho/\rho = 0.25$ when $\rho = 2.0$.

The Rugosity-Insensitive Density System (RIDS)

Because of difficulties in incorporating devices to measure a and b into the sonde, a design was finally chosen that assured that $a = b = 0$. Equation (6) then becomes

$$I = K_1 \rho \exp(-C_1 \rho) + K_2 \rho^2 \exp(-C_2 \rho), \quad (15)$$

where C_1 and C_2 are appropriate combinations of distances and attenuation coefficients; double scattering—Eq. (7)—is included.

Numerical integration gives a value of 3.45 for C_1 at the energies, angles, and distances used in our sonde. Calibration gives values for C_2 , K_1 , and K_2 by a least-squares fit to four known-density blocks. Thus,

$$I = 114,090 \rho e^{-3.45\rho} + 44,964 \rho^2 e^{-2.6\rho} \quad (16)$$

for a particular calibration. This fit, however, is virtually identical to the fit to a simpler expression,

$$I = 83,372 \rho e^{-2.45\rho}, \quad (17)$$

for all densities greater than 0.85 (refer to Fig. 3). Consequently, Eq. (17) is suitable for general use, and an error analysis may be performed on it. (A three-term fit, involving triple scattering, was not attempted, both because there seemed to be no need for it and because, since the scattering cross section would be cubed, the third term would presumably be small.) One finds, upon taking derivatives, that

$$\frac{d\rho}{\rho} = - \frac{1}{1 - C_1 \rho} \frac{dI}{I} \quad (18)$$

Fig. 3. Count rate vs density for Eq. (16) ($I = 114,090 \rho e^{-3.45\rho} + 44,964 \rho^2 e^{-2.6\rho}$) and (17) ($I = 83,372 \rho e^{-2.45\rho}$). Calibration points are shown.

for an expression of the form of Eq. (17); at a density of 2.0 g/cm^3 this gives, for the RIDS,

$$d\rho/\rho = 0.256 \text{ dl/L.}$$

This density error for a given count error (or sensitivity) is comparable with sensitivities for other density systems, the main difference being the elimination of the gap problem.

An attempt was made to calculate the RIDS on a Monte Carlo code, but it was unsuccessful because of the very low ratio of accepted to incident counts.

Generally, in reducing data, the various μ values are taken as functions only of the energy, and mean values are chosen for incident and scattered energies. It must be recognized that chemistry does have some effect, since while most scattering at the energies of interest is Compton scattering, some photoelectric absorption does take place, and a chemical effect obtains. Changes in μ can cause a 2 to 3% change in C_1 and C_2 , depending on material, even in low-atomic-number media, and if one element predominates, its effect should be recognized in data reduction.

Also, as stated above, the density measured by this predominately Compton scattering technique is electron density,

$$\rho_{\text{elec}} = \rho_{\text{mass}}(2Z/A), \quad (19)$$

where Z is atomic number and A is atomic weight. (Z and A must be summed over all elements for a mixture.)

Multiple scattering can be considered a perturbation, but it appears that in practice it can be accounted for explicitly (see below).

The other major perturbation is non-uniform density. Equation (6) distin-

guishes between density in the single-scattering volume and in the rest of the medium. In an actual measurement, unless such a difference is known to exist, there is no way of recognizing it, and ρ_{sv} is assumed equal to ρ_m . If in fact $\rho_{\text{sv}} > \rho_m$, then $\rho_{\text{meas}} < \rho_m$, and vice versa. (The two-detector system is affected somewhat less by this phenomenon.) For example, if the system were to be used to study the density of cement behind casing in a hole, and the single-scattering volume were sometimes in the cement and sometimes in the formation, false results could occur. Happily, because of multiple scattering, the effect is much less pronounced than it would be if all accepted gammas were single-scattered.

Downhole background, if different from that at the surface, can perturb the results if the source is not strong enough to overwhelm it. Using a weak source also results in poor accuracy at high densities, since statistical fluctuation in the count is significant, and the signal-to-noise ratio is poor.

Design of the RIDS

Mechanical

At first it was desired to measure a and b directly. Many methods such as sonar, radar, capacitance, optics, and magnetism, were considered and for one reason or another rejected. Development was undertaken on a mechanical method similar to that of Baker et al.²⁰ However, we were unable to build a mechanical indicator that would measure a and b in the beam path without interfering significantly with the count rate and that would also

work under borehole conditions. Therefore, the sonde was fitted with protuberances or "bumps" over the collimators with strain gages in the covers that would give a signal when the bumps were in contact with the borehole wall. Then and only then would a reading be taken. This requirement made it necessary for the sonde to be used while stationary, not while moving. Considerable tinkering was required before the strain gages could be made reliable and significantly more sensitive to push from the radial than from the tangential direction. Some tangential sensitivity still exists. Microswitches with spring-loaded pins were also tried as contact sensors, but the pins quickly clogged.

Figure 4 is a drawing of the "working-part" of the sonde and Fig. 5 is a photograph of the entire sonde that shows the hydraulic clamping mechanism. A motor- and spring-driven arm was used previously (see Fig. 6), but it was by no means as satisfactory.

The sonde, as currently built, will fit in a 13-cm hole, and clamp in a 1.2-m hole. Extensions for holes up to 3 m in diameter are on hand.

No attempt was made in the prototype to keep temperature constant. The sonde was designed to be waterproof, but we have never dared to test this quality.

Nuclear

After some study it was decided to use sodium-activated CsI as the detector. This was chosen in preference to NaI because its counting efficiency for a given size is better, although its resolution (about 14% full width at half maximum at 667 keV) is not as good. A 5-cm-diam,

5-cm-long crystal was used, ^{137}Cs rather than ^{60}Co , the other obvious choice, was used for the source, since shielding was easier, the sonde could be shorter (although a penalty is paid in penetration), counting of the lower-energy scattered gammas was more efficient, and pair production was eliminated.

The distance between source and detector ports was chosen to be 25.4 cm. A 10° conical collimator was used at the source end, and three 0.625-cm-diam holes were used as the collimator at the detector end, again giving a 10° included angle of collimation. The scattering angle was chosen to be 90° . Collimator cutoff, tested with counters and film, was quite sharp.

Tungsten-alloy shielding 10 cm thick was used between source and detector; this seemed quite adequate.

A graded filter, designed to reduce the number of low-energy gammas, surrounded the detector. This, from the outside in, consisted of 0.4-mm Ta, 0.18-mm Ag, and 0.13-mm "Netic," this last also serving as magnetic shielding for the photomultiplier.

The region of acceptance was from 260 to 320 keV, as calculated from the geometry; no allowance was made for detector resolution.

A 1.5-Ci source was used, and counting time was from 4 to 8 min, depending on density of the medium.

Electronic System

Figure 7 is a block diagram of the electronic system as originally designed. The ratemeter-recorder and the scaler are convenient for checking; the tape has not yet been used, but would be advantageous for routine operation.

Fig. 4. Working drawing of the source-detector part of the density sonde. Total diameter is 12.7 cm across "bumps."

Fig. 5. Photograph of the RIDS sonde (new hydraulic version).

Fig. 3. Photograph of the old version of sonde.

Fig. 7. Block diagram of the electronics of the density system, showing both existing and planned equipment.

A multiconductor logging cable, including one coaxial cable, is required.

Digital stabilization is used, and a small ^{137}Cs source is attached to the crystal to serve as an upper stabilization point. Temperature changes of $\pm 10^\circ\text{C}$ in the sonde seem to have no effect on the stabilized spectrum. The pulse height analyzer includes an integrator which is currently used to integrate over the accepted channels and serves as the main data output.

Delay-line amplifiers are used, but with the present source pileup is not a problem, even with 1 km of cable.

Data Treatment

As our understanding of the behavior of the RIDS grew, the data-reduction technique changed. The final computer program, KHAZAD-DUM, has several options. In all cases, a calibration curve is calculated. This could either be of the form of Eq. (6) (with $a = b = 0$ for the calibration, and calibrated to either two points by simultaneous solution of two equations with different ρ , or to four points by a least-squares fit) or of the form of Eq. (15) (with C_1 set equal to 3.45 and the other constants obtained from a least-squares fit). The code can choose the fit that has the smallest rms deviation for the calibration points.

Data for downhole background vs depth are entered in a table, and the background for a given depth is determined by linear interpolation. Measurement of downhole background vs depth is simplified by comparing a few carefully selected measurements to a standard gamma-ray log. If the two sets of data are proportional, the gamma log, with appropriate multiplication, can be entered in a detailed table.

The code assumes that background used in calibration applies to zero depth.

A measurement is then entered, the downhole background is subtracted, and the constants in the exponentials are changed if either $a \neq b \neq 0$ or if μ_m for the measured point is not equal to that for the calibrated points. Then the appropriate equation is solved for ρ by Newton's method. If, however, Newton's method finds a point on the wrong branch of the double-valued curve (see Fig. 3), the maximum ρ for the calibration curve is calculated, and a stepwise iterative method is used to find both solutions.

Capability for plotting several sets of data on the same paper by CRT or Cal-Comp is included, as is capability for using several calibration curves—for example, both Eqs. (6) and (15)—on the same data. Fluid density and μ can be input for nonzero gap situations. Table 1 lists inputs for the code.

Laboratory Tests

Three Angles

A preliminary test of a design for a density log used a laboratory mockup with a ^{137}Cs source and lead bricks with collimator holes. The source collimator was set at three different angles with respect to the detector collimator. An attempt was then made to solve three equations of the form of Eq. (6) with three different values of μ_m . Such a system would require neither contact nor parallelism, since solution of the three equations would yield the distances of the source and the detector from the wall and also the density.

However, it proved impossible to solve the equations. It is clear now, from evidence presented below, that Eq. (6) is in

Table 1. Inputs for KHAZAD-DUM. Each problem requires one header card, as many control cards as there are runs desired (up to five), three calibration cards for each control card, as many data cards as desired, and, finally, a plot instruction card.

Column	Value or type	Effect (or more about value)
HEADER CARD		
1-20	2A10	Title of entire run.
21-30	A10	Date.
31-40	A10	Point from which depth is measured.
41-48	F8	Nominal depth of hole.
49-58	A10	Fluid.
59-78	2A10	Physicist.
79	+	Accepts remarks, card after card, until it finds no number in col 80. Prints these remarks on output and on plot.
CONTROL CARD (One for each run-or each symbol on the Plot)		
1-40	5A8	Title of run.
	All subsequent data on this card 12	
41-42	+	Does not store or plot primary density value.
43-44	+	Stores and plots secondary density value (if 41-42 not +, stores both, using 2 of 5 slots).
45-46	+	Uses previous set of data with new calibration. No downhole data read.
47-48	+	Signifies this is the last set of data or calibration for this problem. After this set looks for plot card.
49-50	+	After gets 47-48 positive, looks for new problem.
51-52	+	Prints calibration curve.
51-52	-	Does not print output data.
53-54	+	Reads densities, depths (2F10.4) until positive value in cols 31-40, then quits.
55-56	+	Converts depths in ft to meters for plotting.
57-58	+	Depths are input in meters.
59-60	+	Fits two-term curve only.
61-62	+	Prints fitting data for two-term curve.
63-64	N	Number of downhole background points.
63-64	98	Uses previous downhole data with background on calibration card.
63-64	99	Uses new downhole data with previous downhole background.
65-66	+	Doesn't print background data.

Table 1 (continued).

Column	Value or type	Effect (or more about value)
CALIBRATION CARDS (Three for each normal data set)		
No. I		
1-10	F10.	Ingoing attenuation coefficient (0.077 for Cs).
11-20	F10.	Outgoing attenuation coefficient (0.108 for Cs).
21-30	F10.	Ingoing attenuation coefficient for fluid.
31-40	F10.	Outgoing attenuation coefficient for fluid.
41-50	F10.	Cosecant of angle of beam, if using gaps, at source end.
51-60	F10.	Cosecant of angle of beam, if using gaps, at source end.
61-70	F10.	Nominal sum of attenuation coefficient for gaps (3.33 for RIDS and Cs).
No. II		
	F10.	Up to five calibration densities, lowest first.
No. III		
	F10.	As many calibration counts as densities on No. II, followed by background count for calibration and downhole (if no downhole background).
DOWNHOLE BACKGROUND CARDS		
1-10	F10.	Counts.
11-20	F10.	Depths: As many cards as specified in columns 63-64 of control card. Do not use zero depth. 0.001 is all right.
DATA CARDS		
1-10	F10.	Counts.
11-20	F10.	Depth.
21-30	F10.	Source gap (cm).
31-40	F10.	Detector gap (cm).
41-50	F10.	Source attenuation coefficient for nonnormal material.
51-60	F10.	Detector attenuation coefficient for nonnormal material.
61-68	A8	Comment.
72	+	This is the last card of the set—MUST be there to end the set, or there will be no output.

Table 1 (continued).

Column	Value or type	Effect (or more about value)
PLOT CARDS		THIS CARD MUST BE PRESENT.
1-10	F10.	Depth interval on one page.
11-20	F10.	Minimum density for plot.
21-30	F10.	Maximum density for plot.
31-40		Ft/inch Calcomp plot.
41-50		Minimum density for Calcomp plot.
51-60		Maximum density for Calcomp plot.
61-70		Second ft/inch Calcomp (second plot).

fact not completely satisfied by the gammas, and that therefore the three equations could not be solved.

$$a = b \neq 0$$

The first tests of the RIDS were made on the assumption that a and b were to be measured and that Eq. (6) would be used. While this project was abandoned, the results are of interest. Table 2 shows the effects of a and b , when included in the calculation, on the accuracy of the

measurements. Calibration was to two points and Eq. (6). It should be noted that the points with large error are near the turnover of the calibration curve. No spectrum stabilization was available at the time these tests were made, so accuracy was to some extent an unknown function of time. Nevertheless, it seems that the proximity measurement technique would have been satisfactory if the measurements could be made.

Single Scattering Assumed

Table 2. Densities from water-aluminum two-point calibration with gaps.

Mate- rial	ρ_e (g/cm ³)	$a = b$ (cm)	ρ Measured (g/cm ³)	Error (%)
Mg	1.74	0	1.85	5.1
Mg	1.74	1.79	1.79	1.7
Mg	1.74	3.59	1.71	2.8
Al	2.62	1.79	2.53	3.4
Al	2.62	3.59	2.48	5.3
Plastic	1.13	0	1.184	4.4
Water	1.11	3.59	0.991	10.7
ZrO	0.62	0	0.596	4.8
ZrO	0.62	1.79	0.671	8.0
ZrO	0.62	3.59	0.549	11.3

When it was determined to set $a = b = 0$, four calibration blocks were constructed. Two were aluminum and magnesium, with electron densities of 2.62 and 1.74 g/cm³, respectively. The other two were both mixtures of silica with a small amount of epoxy binder; they had electron densities of 1.23 and 0.58 g/cm³.²¹ For this and all subsequent work, a small ¹³⁷Cs source was attached to the detector and digital stabilization was used. A calibration source has the disadvantage that its backscatter peak is near the region of acceptance, and consequently the background was increased greatly, from

35.7 counts/min without the source to 235 counts/min with it.

It was found that a fit of Eq. (6) to any two of these points invariably gave a bad fit to one of the others. It was also found, as anticipated, that it did not matter whether the tool was on a flat face of a block, or in a half-round groove 15 cm in diameter.

To correct for the poor fit problem, a least-squares fit was made to Eq. (6) for all four blocks. Figure 3 shows the fitted curve, the measured data points, and the measured count for a piece of glass foam of electron density 0.14 g/cm^3 . The fit

$$I = 83,372\rho e^{-2.45\rho} \quad (17)$$

for a typical calibration appeared to work quite well, but it was unsatisfactory because the numerical integration required $C = 3.45$ in the exponent.

Multiple Scattering Assumed

A fit to Eq. (15) was forced, with $C_1 = 3.45$, and the result

$$I = 114,090\rho e^{-3.45\rho} + 44,964\rho^2 e^{-2.6\rho} \quad (16)$$

plotted over Eq. (17) over most of the range (see Fig. 3). It remained to perform an experiment that would demonstrate which equation was correct. A sandbox was constructed in which a block of foam or aluminum whose cross section was that of the scattering volume shown in Fig. 2 could be inserted in place of sand at the scattering volume. Monterey sand and magnetite sand were used, and densities were determined by weighing. The counts agreed with Eq. (16) within 3% at worst. Figure 8 shows the recorded spectra for Monterey sand.

From these experiments it may be concluded that Eq. (16) is substantially correct. One may then calculate what percentage of the total corrected count is due to single scattering: 77% at $\rho = 0.5$, 32% at $\rho = 1.5$, and 11% at $\rho = 2.5$.

It can also be recognized that since C_2 is significantly less than C_1 , either the multiple scattering path is shorter than the single, or the energies are higher. Figure 9 shows spectra (with background subtracted) from the second quadrant of the analyzer, for the four calibration blocks. It can be seen that at $\rho = 0.58$ the peak falls almost completely in the region of acceptance, while at higher density the peak moves forward in energy, suggesting the latter cause (i.e., higher energies) for the lower C_2 . One might suggest that the acceptance region be widened, especially in view of the inherent energy error in the crystal, but this would only serve to decrease the slope of the calibration curve and thus reduce sensitivity.

Field Tests

The RIDS has been tested in many holes at the Nevada Test Site. It is quite slow in operation. In steady logging, 10 to 12 points per hour can be logged, but when downhole background and careful calibration are included, the average becomes 5 to 6 points per hour of time spent. Distance logged depends, of course, on point spacing. With the current system, at least one physicist or electronic engineer is required to be present at all times to be sure by observing pulse shape and spectrum shape that the equipment is operating properly.

The authors are not competent to evaluate core data, but in those sections

Fig. 8. Counts in 8 min vs energy (smoothed) for the experiment in which various materials were placed in the single-scattering volume. The medium was Monterey sand (2 keV/channel).

of holes where the geologists claim that the core data are good, the RIDS generally agrees with them to within a few percent. RIDS results have also been compared with those from other logging systems; in fairly smooth sections of hole, with no bad washouts, agreement is also within a few percent. Some particularly interesting tests are discussed below.

Alluvium

Tests were run in desert alluvium at the Nevada Test Site. In one hole, our results were invariably higher than those of a diffusion-type system (see Fig. 10). It was noticed that the bumps on the RIDS

were coated with mud after each run except on the contact surfaces themselves, and it was hypothesized that the RIDS, being less sensitive to mudcake than a diffusion sonde, and penetrating the mud with the bumps, was seeing the correct density.

This hole was logged many times over a period of nine months. A spread of about 5% in density at a given depth was measured. This spread can be attributed either to real differences in density caused by slight depth variations in the tool, changes in azimuth, and drying of the hole, or else to measurement error. We cannot distinguish among these possibilities, but since we know that the

Fig. 9. Counts in 8 min vs energy (smoothed), with background subtracted, for the four standard calibration blocks (2 keV/channel). 14% error in energy is shown.

system is accurate in test blocks and sand, it may be stated that the repeatability in density measured by the system in this hole is $\pm 2.5\%$. In the absence of a rough-walled test well in a medium of well-known densities, no other statements can be made with certainty.

Later a hole that had been drilled with air with a detergent-bentonite additive (Davis mix) was logged. A much smaller mudcake results from such drilling than from drilling with mud. In this situation (see Fig. 11) the RIDS agreed well with the diffusion log, tending to confirm the hypothesis above.

Fig. 10. The RIDS compared with a diffusion log in a hole drilled with mud in desert aluvium.

Ash Flow

As part of a search for a high-porosity dry medium, measurements were made in a low-density ash flow in which the hole was extremely rough (Fig. 12 is part of the caliper log). Figure 13 shows the results. Cores could not be obtained from this hole, but measurements made

on powder (which, we are told, are not too reliable) are shown, and appear to agree fairly well in most places. Agreement with core from another hole, which is supposed to be in the same formation, was also good. In addition, the U. S. Geological Survey performed borehole gravimetry in this hole.²² There may be

Fig. 11. The RIDS compared with a diffusion log in a hole drilled with air and detergent in desert alluvium.

a small error in their free-air gradient,²³ since they did not have the opportunity to measure it at this site, but agreement

with the RIDS is fairly good. Attempts were made to compare results of other logging systems with those of the RIDS in

Fig. 12. A caliper log of a hole in an ash flow surrounded by tuff and rhyolite.

this hole but, according to the loggers, the data could not be properly corrected for gap and caliper in this section. RIDS densities may be low by as much as 3%, since no correction was made for down-hole background, which was found nearby later. RIDS data from two other nearby holes also agree well with those shown,

Fig. 13. Composite of results of the RIDS, borehole gravimeter, and laboratory measurements on powder (blown to the surface in air drilling) in the same hole in an ash flow.

but no comparative data were taken with other density systems in those holes.

Tuff and Rhyolite

A very detailed log was run in a hole through alternating sections of tuff and

rhyolite. Figure 14 compares the caliper and our density log for this hole. It is the most detailed log that has been run to date, it is fully corrected for downhole background, and it shows the geology in sufficient detail for the bases of the volcanic flows to be seen and understood.

Mark III

A new model of the RIDS, capable of operating to 250°F and 3000 psi and having a source strength of 10 Ci, was to have been built by LRI, Berkeley. Many of the defects of the present system were to have been corrected in the new design. So far this has not been done.

Conclusions

The RIDS is an effective system for measuring in situ densities in very rough holes, probably with an error of no more than $\pm 2.5\%$ over most of its range. Being a station sonde, it cannot replace continuous systems for normal use, but in situations in which other systems may fail, the RIDS often succeeds.

DENSITY DATA REDUCTION FOR A DIFFUSION TOOL

Most of the density logging at the test site, and to date, all of it off the test site, has been done with commercial density logging equipment. The best equipment is the two-receiver type, discussed above. When run in a fairly smooth hole, its internal correction appears satisfactory. The current (1969) NTS contractor, Birdwell, uses a diffusion system, also discussed above.

The density logs supplied by this contractor are in a form of kilocounts vs depth. The purpose of the density reduc-

tion programs is to convert kilocount data to gap-compensated density.

The method used is based on empirical curves supplied by Birdwell.²⁴ Each log is calibrated before and after each run by placing the tool on a constant-density block and measuring the count rate. Usually, two calibration points are used, aluminum and magnesium. These points are plotted on semilog paper and joined by a straight line (see Fig. 15).

The relation from this graph is then

$$\rho_x = \frac{\log \left[\frac{\text{Count } x}{\text{Count } 1} \right]}{\log \left[\frac{\text{Count } 2}{\text{Count } 1} \right]} (\rho_2 - \rho_1) + \rho_1, \quad (20)$$

where 1 corresponds to aluminum, 2 to magnesium, and x to the value in question. This formula is used in the code to convert to density units.

Since the density sonde does not maintain constant contact with the wall of the hole, Birdwell has incorporated a proximity wheel that measures the position of the top of the sonde from zero to one inch of gap. (See Fig. 16.) The tool is built so that the toe of the instrument usually rides continuously against the side of the hole. The zone of gamma penetration is approximately one-third the distance from the toe (A) to the proximity wheel (C), indicating that the true gap at the measurement point (B) is approximately one-third the proximity wheel reading. This gives the relationship $b_B = b_C/3$, where b_C is the measured gap corrected for a time constant (see the discussion in the next section). A sonde with a wheel at each end has been built that substantially confirms this assumption.

Birdwell has supplied a set of correction curves for b_B . These curves were

Fig. 14. A caliper log of a hole through sections of tuff and rhyolite shown with the density log of the same hole.

Fig. 15. Standard diffusion log calibration curve.

Fig. 16. Sketch of diffusion sonde showing the proximity wheel.

derived for wet and dry holes and are seen in Figs. 17 and 18. These curves indicate a single intersection point for the

family of true vs observed density curves at each gap. The slope of these lines was empirically observed to be a function of

Fig. 17. Standard gap correction curves for wet holes.

Fig. 18. Standard gap correction curves for dry holes.

b, so a mathematical expression for gap correction is

$$\text{Corrected } \rho = \left[K_1 (b_C \cdot 3)^2 + (b_C \cdot 3 + 1) \right] \times [\rho_v - K_2] + K_3 \quad (21)$$

where

ρ_x = density from calibration Eq. (20)

and

Dry hole: $K_1 = 1.406$

$K_2 = K_3 = 1.286$

Wet hole: $K_1 = 0$

$K_2 = K_3 = 1.525$

The validity of this correction method is discussed in some detail in a later section, which proposes a correction scheme incorporating the dead time of the detector. (Figure 28 shows the effect of this problem.)

The Birdwell curves are approximately correct above 1.7 g/cm^3 , which is reasonably good for most field work. Figure 19 is a plotted sample of densities with and without gap correction.

The corrections for gap caused noise from the gap curve to be incorporated into the corrected data. This problem has been dealt with as explained in the next section.

TIME-CONSTANT CORRECTION OF THE GAP

The calculation of density data, $\rho = f(\text{gap, kilocounts})$ from two or more traces, results in the incorporation of noise when fast response gap data are used with slow response kilocount data. The problem may be approached by converting the slow response data to the fast response system or the reverse. Since the gap-measuring instrument can be overdriven to introduce other noise in the

data, the reduction of the gap trace to the slower response of the kilocounts trace appeared to be the better approach. The process is to convert the gap trace with a model of an electrical filter using the same time constant as the counting circuit for the kilocounts trace.

The method used to solve this problem is to express the ratio of the input voltage to the output voltage across a typical RC circuit as shown in Fig. 20. This circuit, or its mathematical equivalent, represents the nuclear rate counter.

The voltage equations are first expressed in terms of their Laplace transforms.

$$ei(t) = Ri(t) + \frac{1}{C} \int_{-\infty}^T idt \quad (22)$$

converts to

$$Ei(s) = I(p) \left(R + \frac{1}{Cp} \right)$$

and

$$eo(t) = \frac{1}{C} \int_{-\infty}^T idt$$

converts to

$$Eo(p) = I(p) \left(\frac{1}{Cp} \right).$$

The transfer function is then

$$\frac{Eo(p)}{Ei(p)} = \frac{1/RC}{p + 1/RC} \quad (23)$$

RC is the time constant of the circuit
p is the Laplace variable. The logs are all expressed as functions of depth and may be converted to the depth domain by the logging velocity.

RC = time constant in seconds.

Lv = logging velocity of the tool in the hole.

Dc = corresponding depth constant in feet, where $Dc = Lv \cdot RC$.

Fig. 19. LRI plot of raw and corrected diffusion density logs. (+ indicates unacceptable point).

Fig. 20. Equivalent circuit illustrating time-constant correction.

So that

$$\frac{E_o(p)}{E_i(p)} = \frac{1/Dc}{p + 1/Dc} \quad (24)$$

The values of Y :

$Y_o(p)$ = the output transform of gap in inches,

$Y_i(p)$ = the input transform of gap in inches.

D will be referred to as the depth axis that is to be transformed. Y_o and Y_i will be used in place of E_o and E_i , respectively, so that the final form of the transfer function is

$$\frac{Y_o(p)}{Y_i(p)} = \frac{1/Dc}{p + 1/Dc} \quad (25)$$

Figure 21 shows the general case of the variable Y_i . The input function is of the slope-intercept form, where the slope M is the slope of the line between data points and the intercept is the difference between the smoothed value of gap and the input value of gap, or $(Y_{i1} - Y_{o1})$. The

driving function may be visualized as a combination slope and step function input referenced to the point (D_{o1}, Y_{o1}) , where $D_{o1} = D_{i1}$, and $D_{i2} = D_{o2}$. Since the filtered and true points are evaluated at the same depth, the expression for the input function is

$$Y_i = M(Dx - D_{i1}) + Y_{i1} - Y_{o1}$$

where slope $M = (Y_{i2} - Y_{i1}) / (D_{i2} - D_{i1})$
The transform of Y_i becomes

$$Y_i(p) = \underbrace{\frac{M}{p^2}}_{\text{slope function}} + \underbrace{\frac{Y_{i1} - Y_{o1}}{p}}_{\text{step function}} \quad (26)$$

Equations (25) and (26) combine to form

$$Y_o(p) = \frac{Y_i(p)/Dc}{p + 1/Dc}$$

$$Y_o(p) = \frac{M/Dc}{p^2(p + 1/Dc)} + \frac{(Y_{i1} - Y_{o1})}{p(p + 1/Dc)}$$

Fig. 21. Raw and time-constant-corrected gap data compared.

Converting to partial fractions,

$$\frac{M'Dc + p \frac{(Y_{i1} - Y_{o1})}{Dc}}{p^2 (p + 1/Dc)} = \frac{A}{p} + \frac{B}{p^2} + \frac{E}{p + 1/Dc}$$

and solving for A, B, and E,

$$A = (Y_{i1} - Y_{o1}) - M'Dc$$

$$B = M$$

$$E = -(Y_{i1} - Y_{o1}) + M'Dc,$$

resulting in

$$Y_o(p) = \frac{(Y_{i1} - Y_{o1}) - M'Dc}{p} + \frac{M}{p^2} + \frac{M'Dc - (Y_{i1} - Y_{o1})}{p + 1/Dc}$$

The inverse transform of $Y_o(p)$ with respect to the reference point (D_{o1}, Y_{o1}) i.e.,

$$Y = (x - D_{i1}),$$

is

$$Y_o = M(Dx - D_{i1}) + [(Y_{i1} - Y_{o1}) - M'Dc]$$

$$\times \left[1 - e^{-\frac{1}{Dc}(Dx - D_{i1})} \right]$$

To transfer back to the coordinates of the log, the total gap is equal to the response value (Y_o) plus the value of the reference point (Y_{o1}).

$$Y_{\text{Filtered}} = Y_o + Y_{o1}$$

The final form is

$$Y_{\text{Filtered}} = M(Dx - D_{i1}) + [(Y_{i1} - Y_{o1}) - M'Dc] \times \left[1 - e^{-\frac{1}{Dc}(Dx - D_{i1})} \right] + Y_{o1} \quad (27)$$

Figure 22 shows an example of a computer test run using the above formula and calculating intermediate values.

Computerized processing of data through the above formula brought certain problems to light that other programs must consider.

- (1) The data should be processed sequentially in the same direction (up-down) that the logging tool was run.
- (2) The terms $M'Dc$ and $e^{-1/Dc(Dx - D_{i1})}$ are sensitive to the direction of logging. Where $(Dx - D_{i1})$ is negative, Dc must be negative.

Fig. 22. Computed time-constant data.

- (3) Error in digitizing points, where a depth reversal occurs, causes e to go to a positive power. This problem could be solved by using the absolute value function of the power, but then another problem occurs where there are several data points at, or close to, the same depth. The scatter or noise in depth location causes $[1 - e^{-ABS F(f(D))}]$ to decrease in value. The problem was solved for small reversals by adjusting the sign of the power to the direction of the log and then allowing depth reversals to take place. The small reversals tend to stabilize the values of response calculated at the same depth. As of yet, no routines have been written to handle large depth reversals encountered as a result of Grafacon digitizing system error.⁶⁶
- (4) It should be remembered that the depth constant must be changed to compensate for significant changes in the logging velocity in the hole. Logging velocity may be calculated

from the time marks recorded at the side of the log.

A further problem is encountered with values looked up on the filtered log trace. In the density log, for example, a value of gap looked up for a density value, will lie on the line between two filtered gap values. In most cases, this would be valid except where a step-like response occurs in the raw gap log. The interpolated data (shown in Fig. 23 as triangles) will fall on a ramp in the step input, instead of showing a response to the step (solid line).

One method being used now to solve this is to calculate the response for any looked-up gap value. This requires looking up one smoothed value and the original raw gap value. The same formula is used as before in Eq. (27).

A second method would be to store the nuclear count rate in core, and then look up the count rate at each gap value. Usually this method will sacrifice curve character in the density log where gap values are sometimes far apart.

At present, the density logs being run on the Grafacon are correcting densities by adjusting the time constant of the trace.

Fig. 23. Sketch of the problem of interpolation of a time-constant correction responding to a step function.

The problem still needs the following study and corrections:

- (1) A study of the effect of time lag between detector and source for a given depth.
- (2) A study of response of a step density change between the source and detector.
- (3) A study of the response of a step density with thickness less than 19 in.
- (4) A gap correction for count rate instead of density needs to be developed so that response of the two curves will be ideally matched for common depth corrections.
- (5) The caliper log information should be included in the calculation in order to determine if the gap gage is measuring the slant of the tool or parallel gap.

A STUDY OF DEAD TIME AND GAP CORRECTION

While the correction method without dead time correction (discussed in the two preceding sections) provides some improvement, it is based on calibrations at two densities, 1.74 and 2.62 g/cm³, and straight lines are extrapolated beyond those points. The corrections in the section above are derived from those lines, and with an assumption that, to compensate for the assumed tilt of the sonde in the hole, one third of these corrections (made with the sonde parallel to the calibration block) should be used.

Since the validity of these curves seemed questionable, a new set of experiments was carried out with the bottom end of the tool touching the calibration

block, in the probable downhole configuration, and using a third calibration block of density 1.465.

These measurements used a 50-mCi ⁶⁰Co source and 200- and 400-mCi ¹³⁷Cs sources. Somewhat later, a set of proximity runs were made, with the 50-mCi ⁶⁰Co source, the 200-mCi ¹³⁷Cs source, and a ¹³⁷Cs source thought to be 800 mCi. Care was taken to define the position of the tool in the calibration blocks. However, the calibration curves disagreed with those for the previous run. The internal consistency of the data was also somewhat questionable.

Therefore, another set of curves was run with the Co source and with 400 and "800" mCi of Cs. In this set, a calibration curve was run, and then the proximity experiments were done. Unfortunately, the calibration points disagreed with the zero gap points (which should be identical).

As a consequence, another set of proximity experiments was run with the Co source and the "800"-mCi Cs source. These data seem acceptable.

One conclusion can be reached immediately. To obtain good data, the source should not be removed from the tool between the before-run calibration, the runs in the hole, and the after-run calibrations.

Dead Time

Since all sets of measurements show a maximum measured count (see Fig. 24) (different for each set) that apparently cannot be exceeded, it is evident that the density sondes are "paralyzable systems," which presumably satisfy $n = Ne^{-N\tau}$ where n is measured count, N is true

Fig. 24. Raw counts vs gap and density, showing the maximum possible count.

count, and τ is dead time. Then $n_{\max} = 1/\epsilon\tau$. In the proximity experiments, $n_{\max}$ varied between 59 and 55 kilocounts/min, corresponding to τ of 375 and 402 μsec .

The τ known, curves of N vs n may be drawn (see Fig. 25), and the true count N may then be determined from the measured count n . Figure 26 shows calibration curves drawn from raw count on 200 and "800" mCi ^{137}Cs and 50 mCi ^{60}Co . Both a smooth curve and a conventional straight line drawn through the two normal calibration points are shown. The two Cs curves appear quite dissimilar. Figure 27 shows the same data corrected for dead time, with $\tau = 402 \mu\text{s}$ used for the 800 mCi Cs and the Co, and $375 \mu\text{s}$ used for the 200 mCi Cs. (These values

Fig. 25. Dead-time correction curves for various maxima.

Fig. 26. Calibration curves for 200 and "800" mCi of ^{137}Cs .

were obtained from observed n_{max} and are reasonable for Geiger counters.) Note that all calibrations are now straight lines, showing a pure exponential relationship, and that the two Cs curves are essentially parallel. On the other hand, the "800"-mCi Cs line shows counts only 2.31 times the value of the 200-mCi line,

indicating that its effective strength is only about 460 mCi. Possible explanations for this include self-absorption and shielding by the mounting.

In any case, correcting for dead time determined by n_{max} reconciles the various Cs calibration curves and eliminates their curvature. The 400-mCi

Fig. 27. Calibration curves for ^{137}Cs corrected for dead time.

curve is also reconciled by this correction.

Proximity Corrections

When plots of observed density vs true density, similar to Fig. 18 are drawn including the 1.465 g/cm^3 point, strange-looking curves result. Figure 28 is such

Fig. 28. Gap correction curves assuming straight lines on the calibration plot (dry hole) with three densities used. No dead time correction.

a plot for the "800"-mCi Cs source, where observed density is obtained from the conventional straight-line calibration.

Figure 29 is a similar plot, but observed density is taken using the smooth curve drawn through all three points. Three things can immediately be seen. First, using the two-point line gives quite different results from those obtained using the curve. Second, below a density of about 1.65 g/cm^3 , only ambiguous results are obtained. Finally, both sets differ

markedly from the set in current use, as shown in Fig. 18. The sets are also different for different sources. It is clear from these curves that the common (I.R.L.) practice of accepting minimum counts in a section of hole as indicative of true density is often unsatisfactory.

To draw the curves in Figs. 28 and 29, it was necessary to plot count rate vs gap for varying densities, since the original data have different "measured" gaps for each calibration block. (This is because the gaps of $1/4$ in., $1/2$ in., etc., were measured from the ends of blocks of different lengths.) When this is done for true count vs gap, curves as in Fig. 30 result. These are very close to straight lines, and indicate that $N = K e^{C(\rho)b}$, where N is true count, ρ is density, and b is the gap in inches.

When true count vs density for constant gap is plotted, sets of almost straight lines such as Figs. 31 and 32 result, indicating that $N = Q e^{-R(b)\rho}$.

If the lines in Fig. 31 are prolonged, they almost meet in a point. If it is assumed that they do, two exponentials can be combined to give

$$N = N_0 e^{-(K_0 \cdot E b)(\rho - \rho_0)}$$

where N_0 is the count at the meeting point, ρ_0 is the density at that point, K_0 is the slope of the zero-gap line, and E is a constant.

It was desired to test this concept, so the constants were determined from the top and bottom lines of Fig. 33. K_0 was found to be 2.28, E was 0.66, and ρ_0 was 0.97. Since Fig. 33 was made from interpolated gap data, the expression was then tested with the original raw data for both 800 and 300 mCi Cs. The result is

Fig. 29. Gap correction curves with curves fitted through the three calibration points (dry hole). No dead time correction.

shown in Fig. 34, where count is plotted against $(2.28 + 0.66b)(\rho - 0.97)$ and, to all intents and purposes, straight lines result. This, for hand fitting, is excellent agree-

ment. Note that while the constants were derived for the 800-mCi source, the 200-mCi data also fit a line for all but the largest gaps. The difference in slope is

Fig. 30. True count vs gap for Co and Cs sources.

Fig. 31. True count vs density for various gaps for "800" mCi of ^{137}Cs .

Fig. 32. True count vs density for various gaps for 50 mCi of ^{60}Co .

amenable to two explanations. One is that a hand fit is not the best for the purpose; the other is that there is probably some background effect at high density for the 200-mCi source.

As a final exercise, plots similar to Figs. 28 and 29 were made, with points interpolated at densities of 1.6, 2.0, and 2.3 g/cm^3 calculated from Fig. 34. Figures 35 and 36 are quite different from Figs. 28 and 29.

Recommendations

It is strongly suggested that our new knowledge be used in the future for proximity correction. The first step is to repeat the hand calculations discussed above with a computer, perhaps with more data. It is also strongly recommended that the experiments be repeated with "wet hole" conditions.

The field calibration procedures should be revised to use all three blocks and to

Fig. 33. True count vs density for various gaps for "800" mCi of ^{137}Cs showing the point of intersection.

determine n_{max} . This latter can readily be done by slowly raising the tool with a jig above the 1.465 density block until a maximum is reached. It would also be desirable, if possible, to obtain, say, 1-in. gap points in the field. Care should be taken not to move the source between calibration and measurement.

After this calibration, τ can be determined from n_{max} , and true count N (still of course, double-valued) determined from measured count n . Then a curve such as the one in Fig. 34 can be entered with true count and gap to determine true density.

All of this is, of course, based on the assumption that the bottom of the tool touches the borehole wall, but this is probably the best assumption that can be made.

As a longer-range project, it is suggested that the tools be rebuilt as non-paralyzable systems, or at least so that τ is constant from day to day.

ON THE EFFECT OF DRILLING FLUID ON MEASURED DENSITY IN ALLUVIUM

Some time ago, R. D. Carroll of the United States Geological Survey pointed out that drilling fluid, invading alluvium,

Fig. 34. A fit to $N = N_0 \exp(-(K_0 + Eb)(\rho - \rho_0))$.

Fig. 35. Gap correction curves with interpolations from Fig. 34 (straight calibration).

Fig. 36. Gap correction curves with interpolations from Fig. 34 (curve calibration).

would give rise to a measured density significantly higher than the true in situ

density. This, presumably, would occur whatever density measuring method was used (except for gravimetry), unless the hole was drilled dry.

Somewhat more recently, in October 1966, a set of logs was run in hole Ue2y at the Nevada Test Site. These logs have now been studied, and certain ones appear to show quite clearly the effect predicted by Carroll. Many logs were run, but only eight are of interest in this context. They will be discussed by run number for future reference.

Runs 5, 6, and 7 have overlapping sections in a region of the hole that was drilled with Davis mix. Run 5 was made before the hole was blown out, run 6 after it was blown dry, and run 7 after it was refilled with mud. After gap corrections (the gap being quite small), no significant difference can be seen among the logs from depths of 270 to 550 ft.

Runs 10, 13, and 14, shown in Figs. 37 and 38, were run in a section (from 570 to 792 ft) that was drilled dry (run 10), then a deeper section drilled with Davis mix (run 13), and then the hole filled with mud (run 14). Densities in all runs but run 10 have been corrected for gap with the wet hole correction, to be conservative and to minimize the correction. In run 10, the dry-hole correction was used.

Run 14 is not significantly different from run 13. Some of the gaps seem to have filled up with mudcake, or the azimuth is different. It may be estimated that drilling with Davis mix yields an

* The U. S. Geological Survey recently reported on gravimetry data in this hole. Their measured density varied between 1.9 and 2.1 g/cm³—higher than would be expected from the following discussion.

10 and 13 (October 1966) of a section of hole Ue2y. The logger 1; proximity corrections were made by the authors.

15% higher than
 ay be further con-
 had time to pene-
 e a significantly
 ty in the alluvium

(May 1967), the
 19), blown dry,

and logged again (run 20). The two logs
 are essentially the same, and fall between
 runs 10 and 14—apparent density after
 seven months of mud is less than that with
 one day of mud! Assuming that the tools
 were functioning correctly at all times,
 two plausible explanations can be put
 forward. Either a mudcake formed that

Fig. 38. Density logs 14 (October 1966) and 19 (May 1967) of a section of hole Ue2y. The logger was Birdwell; proximity corrections were made by the authors.

lowered the apparent density, or else the mudcake formed and became waterproof, the water diffused away from outside the mudcake, and no water from the hole penetrated the mudcake to replace it.

Of course, only one set of logs has been run in one hole, so these results must be considered preliminary, but at least some estimate of the magnitude of the effect can now be made.

Acoustic Velocity

To perform computer calculations concerning the effects of underground nuclear explosions, fairly accurate knowledge of compressional and shear wave velocities is required.⁴ It is important that these properties be measured in situ. In general, these measurements may be classified into two major groups, corresponding respectively to the macroscopic and microscopic points of view.

UPHOLE AND DOWNHOLE SURVEYS. WITH EXPLOSIVES

The macroscopic point of view deals with getting an average value for a large bulk of material with only a secondary interest in variations within the material. Standard methods of measuring compressional wave velocities from this point of view involve seismic surveys in which an explosive is detonated and the resulting seismic waves are recorded by detectors placed a known distance from the source. Data intervals are generally 10 to 100 m. Time resolution is limited to $\pm 1-2$ msec by inaccuracies in the zero-time signal generated by the blasting system and the narrow band pass, 5 to 100 Hz, of the amplifying and recording equipment. Unfortunately, such a system does not suit our needs, as we generally require data intervals of 1 to 10 m and therefore a time-resolution of $\pm 0.1-0.2$ msec. Also, standard methods of obtaining shear-wave velocities are very limited. Therefore, we have developed high-resolution recording systems and are doing experimental work on shear velocities.

Improved Firing System

In a standard seismic blaster system, a capacitor is discharged across a seismic-cap bridge wire, which heats and detonates a temperature-sensitive primer. A zero-time signal is generated at the instant the capacitor is discharged; this signal can precede the actual cap firing by $1/2$ to 2 msec, depending on the make and model of the cap, the applied firing voltage, and the loop resistance of the firing line.

Early in our work we used an exploding-wire detonator.²⁵ These provide a zero-time accuracy of a few microseconds, but they are expensive and require cables that are costly to prepare. Accurate work has been done in the past with caps, but three wires and a downhole blaster are required.²⁶ This is unsatisfactory for a long string of charges, especially when the hole must be stemmed with sand, since the blaster is destroyed.

Accordingly, we built a firing unit (see Fig. 39) that gradually applies voltage to the bridge wire of a conventional seismic cap. No transient signals are generated until the firing line is broken by the explosion. The current in the firing line is monitored through a high-pass filter; thus, the initial application of voltage is not seen on the output of this filter, but the wire rupture is seen quite well. The pulse is displayed as zero time on an oscillograph.

Figure 40 shows the original and modified circuits of a Geospace portable firing unit that is used whenever possible. The peak firing current of the Geospace unit

Rear panel
Amphenol - M5 3102 A14S-95

Fig. 39. Circuit diagram for the van-mounted firing unit.

Fig. 46. Original and modified circuits of the portable firing system.

is 1.2 A. Both units have been used to perform experiments in which a geophone was placed in contact with a cap. The lag between the time break and the geophone signal arrival was never observed to be more than 0.05 msec.

Surveys are fired in one of two configurations. Often the ordinary "uphole" method is used, with charges at various levels in the hole and with ordinary geophones at or near the surface in other holes. The data from several geophones are averaged to minimize statistical error. This method, however, tends to destroy the hole either by explosive

damage or by plugging with the stemming material. In those cases where the hole must be preserved for future use, a "downhole" survey is made with charges at or near the surface and with detectors in the hole.

In the latter case, if the hole will hold fluid, standard crystal-type pressure-sensitive geophones are used. If the hole will not hold fluid, a lock-in geophone sonde must be used. Such a sonde, manufactured by the Birdwell Company, was purchased. It is a modification of their standard lock-in unit and is capable of recording three orthogonal arrivals, both simultaneously

and separately. This lets us determine the direction of particle motion in the wave. However, this sonde is about 2 m long. Since we must often work in holes whose depth is 50 to 100 m, the uncertainty of ± 1 m in the point of contact of the sonde is unacceptable.

A comparison of a crystal accelerometer and a geophone has been made to test the possible usefulness of the former for downhole work. A high-sensitivity Hall-Sears HS-10 geophone and an Endevco 2215 accelerometer were placed side by side on the floor of the laboratory. Approx-

mately 50 ft away, a foil placed on the floor was struck with a brass tube. Tube-foil contact triggered the recording oscilloscope. The gains of the two channels of the oscilloscope were adjusted until the peak signal was the same for both instruments. Figure 41 shows the result: the accelerometer responds much more quickly (as it should), giving a clearer first arrival.

The experiment was repeated with 2 in. of lead and 1 in. of foam between the foil and the floor to reduce the frequency. Figure 42 shows the record. Again, the accelerometer responds sooner.

Fig. 41. Comparison of the high-frequency responses of a geophone and an accelerometer (2 msec/cm sweep rate).

Fig. 42. Comparison of the low-frequency responses of a geophone and an accelerometer (2 msec/cm sweep rate).

This difference in response is to be expected, since peak acceleration in a signal precedes peak velocity. However, it is more striking than anticipated.

The geophone (and even the smaller HS-1 used in our normal downhole surveys) requires orders of magnitude less amplification. Therefore, for ordinary use (where, after all, arrival time is plotted against distance and a delay will "cancel"), geophones are more satisfactory. But for the ultimate in resolution, the accelerometer would be best.

Lock-in Geophone

A lock-in sonde only 60 cm in overall length was constructed (see Fig. 43). It is quite satisfactory as a detector and is still used occasionally, but it has mechanical problems. A new design has since been built which is quite successful (see Fig. 44). The 10-cm-diam unit carries an array of three geophones, directed orthogonally. This array is coupled to the hole wall by spring-loaded, motor-driven arms that can expand up to 63 cm. The geophones are always the uppermost parts in contact with the wall. Thus, they receive the wave first, and transmission through the body of the sonde presents no problem.

Early recordings of "first-arrivals" at several depths indicated that sound propagation down the cable might be distorting the data. In such a case, cable velocity could be mistaken for formation velocity. To eliminate this interference, a 3-m, soft-nylon strap was placed between the detector and the end of the supporting cable. Signal wires remained connected to the geophone.

Some of the downcoming sonic energy is reflected back up the cable by the impedance mismatch provided at the cable-strap connection. The remaining signal is greatly attenuated, since the nylon strap is slack when the detector is clamped in the hole for the actual measurement.

To measure the effectiveness of this mechanical isolator, tests were made at four depths with a second geophone strapped to the cable at the surface.

First, the sonde was clamped in the hole and, with the cable taut, the cable was struck with a rod and the "cable velocity" (8000 ft/sec) was measured. Then the procedure was repeated with a slack cable, and the amplitudes of the signals at the surface and downhole geophones were measured. Amplifier gains were not changed.

With a slack cable, the amplitude at the downhole detector was 1/5 to 1/25 that measured at the surface detector.

With a slack cable, a shot was fired and the two amplitudes were measured again. During this step, the amplitude of the downhole signal was equal to or greater than that at the surface. This final test indicated that the recorded wave had not come down the cable, for had it done so, the signal at the sonde would have been less than that at the surface.

The tests indicated that the slack isolator attenuated the sound transmitted down the cable sufficiently to prevent interference with the recording of waves propagated through the rock.

Angular Accelerometers

In order to improve our capability for unambiguously detecting shear waves,

Fig. 43. First lock-in geophone Sonde (rubber boot not shown).

angular accelerometers have been considered as detectors.²⁷ We obtained a Systron-Donner Model 4525 with a frequency response of 0 to 100 Hz and a sensitivity of 3.24 V/rad/sec^2 . One test was performed using the swinger (discussed in detail later) as a source, with detectors on the surface at 6, 12, and 18 m from the target. Horizontal geophones were emplaced at each detector location with both radial and tangent axis orientations. The axis of the angular accelerometer was vertical. Figures 45, 46, and 47 show the signals recorded. The results of several "shots" are overplotted to indicate repeatability. Note that the repeatability of the geophone traces is very good, while that of the angular accelerometer is poor. It is apparent, however, that the signal has frequency components outside the specified band pass of the instrument. The specifications also include a sizeable amount of phase shift that may be influencing the data. These units are of the servo type, which accounts for their high sensitivity and limited frequency response. Better results may be obtainable with strain gages or piezoelectric devices, even though the sensitivity would be less.

Another test of this approach was obtained when these units were used on a seismic uphole survey with 1 to 5 lb of high explosives as the source, and the result was compared with a downhole survey using the swinger as the source and the lock-in geophone sonde as the detector.

Both angular accelerometers and horizontal geophones were used on the uphole survey. Data from the angular accelerometers agree fairly well with the swinger (refer to Fig. 67) in the upper 130 ft (values between 3222 and 2941 ft/sec were obtained, depending on how data were "picked"), but the choices are not too objective. Below 130 ft, where many arrivals occur, no convincing values could be obtained. Horizontal geophones were even less satisfactory, with velocities of 2300 and 3500 ft/sec obtained from unconvincing picks. In general, the angular accelerometers should be considered a qualified failure, and the horizontal geophones are an unqualified failure, at this stage. It should be stated that the medium here was highly fractured, nonhomogeneous, and nonisotropic to such a degree that questions arose as to the accuracy of the compressional wave data.

Fig. 44. New lock-in geophone. Sonde small head contains geophones.

Fig. 45. Transverse geophone signals in the angular-accelerometer test.

Fig. 46. Angular-accelerometer signals (showing poor repeatability).

fig. 47. Radial geophone signals in the angular-acceleration test.

Recorders

Signals are recorded on an oscillograph with a paper speed of 300 cm/sec, using amplifiers that are flat from 0 to 20 kHz. Its galvanometers are rated at $\pm 5\%$ at 1 kHz and appear to be satisfactory. Typical records are shown in the experiments section. The signals are also recorded on a 14-channel 150-cm/sec tape recorder with a response of from 0 to 20 kHz. Since small amounts of noise greatly increase the difficulty of making accurate "picks," great attention was given to ground loops and cable shielding in order to reduce electrical noise.

The equipment is mounted in a 6-wheel-drive van along with a 15-kVA, 60-Hz, 110/220-V generator. In order to reduce acoustic and seismic noise, the generator is shut off at shot time, and the seismic system powered through dc-ac inverters from a storage battery consisting of 200 1.25-V nickel-cadmium cells. The cells are recharged automatically when the generator is turned on.

A second recording system consists of a battery-powered unit with 12 channels that is self-contained in a portable box. It was purchased from Geospace Corporation, who modified it to give it a 150 cm/sec sweep speed. The records are made on Polaroid film that can be copied and enlarged to improve the resolution. The firing system was modified as described above. For short-distance measurements, this system is quite satisfactory, but its total sweep time for a ± 0.1 -msec resolution is only 50 msec. For longer records (>0.4 sec), the standard drive system is used. The synchronization error of the sweep with the firing is about 5 msec, so the effective sweep is about 45 msec.

The nominal bandpass of the unit is approximately flat from a few Hz to 500 Hz.

Conventional recorders used by the various companies for normal seismic surveys have a bandpass of 10 to 180 Hz and low paper speeds. Figure 48 is an example of a conventional record recorded on an experiment in rhyolite. Figure 49 is our record for the same project.

Data Reduction

Picking the slow-rising pulse of an initial P-wave arrival has always presented a certain problem in interpreting first breaks. The P-wave usually arrives

Fig. 48. Conventional record from the rhyolite experiment, showing the "first break" (500-Hz timing trace).

Uphole surveys

Fig. 49. Typical record from the rhyolite experiment showing the "first break" (1-kHz timing trace) The time-break cross-talk was later greatly reduced.

at a frequency of well under 100 Hz, depending on lithology and on the distance between the detector and the energy source. This low frequency can extend the breaking period of the arrival to as much as two msec. Conventional records are run at paper speeds of approximately 25 to 37 cm/sec. Combining a 2-msec roll-off with a low paper speed, and in many cases a low signal-to-noise ratio before the first arrival, precludes the $\pm 100\text{-}\mu\text{sec}$ accuracy that is essential to our measurements.

Our interpretation of first arrivals depends on three things: (1) a low pre-arrival noise level, (2) the high sweep or paper speed of the recorder, and (3) the method of choosing the actual break. Our method of picking a first arrival from the slow-rising pulse consists of placing the record (film or paper) under a magnifier and scribing a line on the top of, and parallel to, the trace to be picked. Our low prearrival noise level permits the

trace and our parallel line to follow very closely. Under magnification, the first departure of the line and the trace can be observed. Actual measurement of the time interval is made with a Gerber variable scale.

This results in a tabulation of arrival time vs depth along with supporting data such as surface elevations, detector or shot offset from the hole being measured, etc.

The next step is to interpret these data in a manner compatible with the hydrodynamic elastic-plastic codes, SOC and TENSOR.

SEISMIC SURVEY DATA REDUCTION CODE

The problem imposed by measured time vs depth data is the construction of a simplified velocity vs depth model for use in explosion effect calculations. Because of errors in arrival time measurements, it is not wise to assume that interval

velocities between successive data points will represent an accurate velocity model. Again, a least-squares fit to the entire data does not indicate layered sections of high or low velocities. A considerable amount of hand "eyeball" effort usually goes into picking depths at which velocity changes (or "break points") in the data occur, and these are often related to the observer's knowledge of the lithology. The purpose of the code, then, is to pick the break points without bias in some statistical fashion, and plot a series of straight-line, least-squares fits to the various velocity intervals.

The code name is STEARNS, an acronym for Seismic Trend Evaluation Allocating Regions by Normalized Statistics. The code is divided into two parts. The first part (SEISCOMP) converts the input data to corrected time vs depth and lists it in a report-sized format. The second part (STEARNS) takes these data and finds the break points and overplots the data with the least-squares fit to the data.

SEISCOMP

The SEISCOMP subroutine reads in the observed travel time at the observed depth of the geophone or energy source, depending on whether it is an uphole or downhole survey. The observed travel time is corrected to its vertical depth component assuming that the vertical travel path is proportional to the true travel paths (see Fig. 50). The calculation of Eq. (28) is performed on each data point, and an output listing is shown in Fig. 51.

Corrected travel time

$$= \frac{\text{Dep} - x}{[(\text{Dep} - x)^2 + F^2]^{1/2}} \times T_{\text{ob}} + \frac{x}{\text{Vel}} \quad (28)$$

where

Uphole:

Dep = observed depth from surface to energy source,

x = vertical distance from surface to near-surface geophone,

F = horizontal offset from hole to energy source,

Fig. 50. Sketch of distances used in travel time correction.

CALCULATION DATA
SEISMIC UPHOLE AND DOWNHOLE LOGGING
EVENT DE200 SCHOONER
HOLE DE200 AVE. HIGH GAIN

TYPE SURVEY UPHOLE			DATE 7 / 01/68		HOLE DEPTH 0756.0			HOLE SIZE		
SHOT NO	SHOT DEP	COR DEP	GEO OFFSET	SHOT TO GEO	COS THETA	Obs TIME	COR TIME	DFL DEP	DFL TIME	INTERVAL VFL
2	345	344	20.0	345.0	.9983	.0778	.0776			
3	300	299	20.0	300.1	.9977	.0700	.0698	45	.0078	5750
4	273	272	20.0	273.2	.9973	.0645	.0643	27	.0055	4893
6	220	219	20.0	220.4	.9958	.0530	.0527	53	.0115	4590
7	195	194	20.0	195.5	.9947	.0466	.0463	25	.0064	3890
8	165	164	20.0	165.7	.9926	.0410	.0415	30	.0047	6300
9	140	139	20.0	140.9	.9898	.0349	.0345	25	.0070	3547
10	115	114	20.0	116.2	.9850	.0272	.0267	25	.0077	3224
11	90	89	20.0	91.7	.9759	.0249	.0243	25	.0074	10025
12	62	61	20.0	64.6	.9500	.0182	.0173	28	.0069	4004
13	35	34	20.0	39.8	.8651	.0142	.0122	27	.0050	5375

Fig. 51. Sample of computer output in the travel time correction.

Vel = surface velocity for distance x ,

T_{ob} = observed travel time over travel distance;

Downhole:

Dep = observed depth from surface to geophone,

x = vertical distance from surface to energy source,

F = horizontal offset from hole to geophone,

Vel = surface velocity for distance x ,

T_{ob} = observed travel time over travel distance.

The input formats for these data are given in Table 3. The corrected time data and corresponding depth data are then transferred to the STEARNS portion of the code.

STEARNS

At the time the STEARNS code was attempted, there was no known statistical tool that could pick the break points in the same manner that the human eye does. The approach to this problem was to fit previously hand-picked velocity data with the code. The programming, statistics, and constants for decision making were continuously changed until acceptable fits could be obtained. As data with greater random time error were used, the differences between the hand picks and the machine picks were seen to be influenced by human a-priori knowledge about other logs in the hole, or other uphole velocity

Table 3. Seiscomp input formats for Stearns.

CARD 1			
Column	Format	Information	Example
1-29	3A8	Event name and location	UE2OU Schooner
25-32	A8	Survey type	Uphole
33-40	A8	Date	7/30/68
41-48	A8	Depth	756 ft
49-56	A8	Hole diam	10 in.
57-80	3A8	Comments on accelerometers	Av of high gain accelerometer
CARD 2			
Column	Format	Information	Comment
1-7	F7.2	X-depth (ft)	Entry will not be used if X-depth on cards 3 through N is greater than zero.
8-14	F7.1	Velocity (ft/sec)	
CARD 3 THROUGH N			
Column	Format	Information	Comment
1-2	I2	HE shot number	
4-10	F7.3	Depth (ft)	
12-18	F7.3	Offset (ft)	
20-24	F5.4	Observed time (sec)	
26-32	F7.3	X-depth (ft)	
34	I1	Last card indicator	1 is the last card in data group 2 is the last data card in the last group 0 or blank for all other cards
LAST CARD			
Column	Format	Information	Comments
1-5	F5.0	Sensitivity values	Up to 10 values may be entered to give a variety of plots. 100 is normal. 300 is insensitive or usually one straight line fit.
6-10	F5.0	Sensitivity values	
11-15	F5.0	Sensitivity values	
16-20	F5.0	Sensitivity values	
21-25	F5.0	Sensitivity values	
26-30	F5.0	Sensitivity values	
31-35	F5.0	Sensitivity values	
36-40	F5.0	Sensitivity values	
41-45	F5.0	Sensitivity values	
46-50	F5.0	Sensitivity values	

logs. An attempt was made to consider more possibilities for fits by assigning a sensitivity value (S) to each plot. Each sensitivity value assigns corresponding values to the program constants and limits (see below). Two methods of approach were tested during the development; each yielded different but still plausible answers. Each sensitivity value produces a plot for each method. Method 1 uses time deviation from the least squares, while method 2 is sensitive to velocity deviations from the least-squares velocity line. See Fig. 54 for method 1 and Fig. 55 for method 2.

The approach to the problem has an intricate set of statistical tradeoffs for picking the break points. The result of these tests is either a pass or fail answer from which a decision is made to pick a new interval for a new test.

Equations Used in STEARNS

The procedure for choosing possible break points is as follows: at each depth point I, a least squares fit to a straight line for all points within a depth interval of length S (sensitivity value), ending at StI, is made, yielding a velocity V(I). Then at each point an "acceleration" $A(I) = [V(I) - V(I+1)]/20S$ is computed. An array of A(I) vs depth is generated, and the local maxima and minima are tested. If $|A(I)|_{\max} > [0.77 + D(I)/2000]/P$, where D(I) is depth and P a noise-dependent weighing factor, D(I) is accepted as a tentative break point, and statistical tests are then applied to choose among break points.

Statistical expressions used in acceptance or rejection of the data are as follows:

TREND Analysis

Acceleration trend²⁸

$$\text{Rank coefficient } RHQ = - \frac{\sum_{i=1}^n d_i^2}{3n - n}, \quad (29)$$

where

n = total number of points,

d_i = difference between actual rank of each velocity interval and sequential rank, i.e., 1, 2, 3, ... n.

SUBTREND Analysis²⁹

$P_{(u)e}$ = probability when u is even

$$P_{(u)e} = 2 \frac{(n_1 - 1)! (n_2 - 1)! n_1! n_2!}{\left(\frac{u}{2} - 1\right)! \left(\frac{u}{2} - 1\right)! \left(n_1 - \frac{u}{2}\right)! \left(n_2 - \frac{u}{2}\right)! N!} \quad (30)$$

$P_{(u)o}$ = probability when u is odd

$$P_{(u)o} = \frac{(n_1 - 1)! (n_2 - 1)! n_1! n_2!}{\left(\frac{u-1}{2}\right)! \left(\frac{u-3}{2}\right)! N!} \times \left[\frac{1}{\left(n_1 - \frac{u+1}{2}\right)! \left(n_2 - \frac{u-1}{2}\right)!} + \frac{1}{\left(n_1 - \frac{u-1}{2}\right)! \left(n_2 - \frac{u+1}{2}\right)!} \right], \quad (31)$$

where

n_1 = number of elements above least squares velocity line,

n_2 = number of elements below least squares velocity line,

u = total number of runs above and below the least squares line.

Standard deviation of velocity

$$= \left[\frac{\sum_{i=1}^n (V_i - \bar{V})^2}{N - 1} \right]^{1/2}, \quad (32)$$

where

$\bar{V}$ = least mean square velocity.

Standard time deviation

$$= \left[\frac{\sum_{i=1}^n (T_i - \bar{T})^2}{N-1} \right]^{1/2} \quad (33)$$

One of the most useful tests in determining acceptance is the standard deviation of velocity test,

$$|\bar{v} - v_x| \geq \left[\frac{\sum_{i=1}^n (v_i - \bar{v})^2}{N-1} \right]^{1/2} \quad (34)$$

where

N = number of line segments,

v_x = velocity of the new segment under test.

This standard deviation test compares the difference between the least-squares velocity line (including the point under test) and the velocity at the end of the interval under test to one standard deviation of the velocities between points in the interval. If the velocity at the end of the interval is outside one standard deviation, then the total interval is not accepted even though it has passed previous statistical tests. This test is useful because it broadens its acceptable limits in noisy data. It may be bypassed by the confidence interval test of the slope or velocity line.

The 80% confidence interval test³⁰ compares the present interval to the previous accepted interval (if any). This test is not performed if this is the first test over new data.

The confidence interval for least squares velocity is given as

$$\bar{v} \pm AN(N) [N-2] \sqrt{\frac{\hat{\sigma}^2}{\sum_{i=1}^n (T_i - \bar{T})^2}} \quad (35)$$

$$\hat{\sigma}^2 = \frac{1}{N-2} \left[\sum_{i=1}^n (D_i - \bar{D})^2 - \frac{\sum_{i=1}^n (D_i - \bar{D})(T_i - \bar{T})^2}{\sum_{i=1}^n (T_i - \bar{T})^2} \right]$$

where

$AN(N)$ are constants that are dependent on the confidence coefficients used and the number of degrees of freedom $(N-2)$,

N = total number of data points in a selected interval,

T = time,

D = depth.

The procedure for interval selection is as follows:

The "acceleration" of the time-distance data is normalized and the peak absolute values of acceleration are recorded as possible break points. Generally, the number of possible break points runs about one-half to two-thirds of the total number of data points. Data that show slow but constant acceleration may present a slight problem in theory, but in practice the noise in the data causes more than an abundant number of possible breaks.

The testing procedure (see below) starts at minimum depth and runs downward. The first test takes the top point to the first apparent break point (insuring that the interval contains at least three data points) and then passes judgment over the interval. If the interval is "good," then the next test is from the top point to the second apparent break point. This procedure continues until the addition of new

data results in a failure. The interval selected prior to the failure is now the accepted interval. The data point above the top of the accepted interval (if any) is then tested for acceptance and is either included or excluded from the acceptable interval. A least-squares line is then plotted over the final "good" interval. This procedure seems to work well when the noise variation in the data and the statistics are well matched, but more serious problems occur where consistent statistical rejection comes from noisy data. As is very often the case, the data noise can be statistically strong enough to mask the break points. The noise problem is treated by first finding a good section of data on the bottom of the bad zone (if any) and then returning to the bad zone with desensitized statistical acceptance. The statistics are continually desensitized until a good portion or all the data can be fitted in the bad zone. Occasionally, this method gives the result that poor data are surrounded by break points that may or may not be valid.

A second problem occurs where break points are chosen for a large interval that is statistically unacceptable. If the interval contains subintervals that have not been tried, then all the subinterval breaks must be investigated before desensitizing the statistics. For the subintervals, the statistics may or may not be sensitized depending on conditions of previous trials.

The complete interaction of all the parts of the program is too involved to mention in detail, but a general flow diagram is provided in Figs. 52 and 53

that explains in terms of pass and fail the decisions occurring through the program.

A pass indicates that the decision is tending toward acceptance and a fail indicates nonacceptance of the interval under test. The reason for the involved flow chart resulted from problems of specific types of statistics related to this problem. The subtrend analysis tended to be very insensitive to small populations, i.e., it would indicate randomness. The rank correlation coefficients, on the other hand, indicated trends for small populations, but not for large populations. If both of these trend statistics indicate random values, then the interval is judged good for a test by Eq. (34). If passed, then further tests for standard deviations of velocity and time are made against given levels, which depend on sensitivity S . If they pass, then the data is given the final test by Eq. (34). If all these tests fail for the new interval, then the program decides whether to plot the preceding good data, increment to a new trial, or increment to new levels of statistical acceptance.

The results of the plot program are shown in Figs. 54 and 55. For each interval, the least-squares velocity is given with a confidence interval of 80%. There are some statistics indicating whether the interval was properly selected or not. The rank correlation test indicates if the velocities are constantly on the increase or decrease through the interval. The rank correlation is used to tell if the interval is under acceleration. The code gives the statement "Acceleration Trend = 0.635." Acceleration is probable if the value indicated by |Acceleration trend|

Fig. 52. Flow chart for the STEARNS code (part 1).

Fig. 53. Flow chart for the STEARNS code (part 2).

Fig. 54. Output of the STEARNS code in the velocity mode at one sensitivity.

>0.5. The value is negative for increasing velocities with depth. A second statement is plotted for the interval if the subtrends are indicated. The code then states that subtrends are present. A third statement is given at the bottom of the page under total time deviation. The value given is for the standard deviation of time for all the data points in all the

intervals. This value will be small for the better data fits, but it may also be small if a large number of intervals fit well. A fourth statement on goodness of fit is indicated by how many line segments are separated by velocity discontinuities or gaps. These gaps are put in by the code when an intersection between adjacent lines cannot be made within the

Fig. 55. Output of the STEARNS code in the time mode (same data and sensitivity as Fig. 54).

depth interval of ± 1 data point of the interval end points. Occasionally, one data point will have gaps on both sides if it belongs neither to the population above nor to the one below. A large number of gaps suggests that velocity changes are present in the fine structure between data points or that the model picked by the code does not fit together well.

Other gaps labeled NO DATA occur when depth between adjacent data points is greater than the sensitivity values input by the user. For example, a sensitivity of 100 would try to fit all data points that are separated by less than 100 ft. Any separation distances greater than 100 ft are bracketed with a no data interval, and the data above or below the

interval cannot belong to the same statistical population.

The user should run this problem with a variety of sensitivity values. The selection of the proper data fit from a set of sensitivity runs is still an a-priori judgment of the individual, but it is now statistically weighted toward the data. Hopefully, this method of automatic data analysis will save time and offer definite selections where doubt prevails.

Future work on this program should probably fall in three categories. The constants dependent on the sensitivity value are not completely in tune at higher sensitivity values. Occasionally, very strange fits occur at sensitivities ranging from 150 to 300. The program was designed around the value of 100 and was made to fit the data model shown in Fig. 56, which was made by R. T. Stearns.³¹ A second base point is needed at a higher sensitivity value to establish the proper linear relationship of the constants.

Secondly, research on other methods of analysis should be investigated. A cross-correlation of a ramp model with varying length from the intersection should be tried for picking break points.

One method that was attempted with a very minimum of programming effort yielded some reasonable results. The velocity statistics for 95% confidence [Eq. (34)] was performed for every length line over three data points long, and for every position in the data. The line interval selection is made with the minimum error region. The next line is selected from the next minimal error region that does not have points belonging to the first selected line, and so on. The choice of 95%

confidence levels may have caused suppression of intervals with a small number of data points, but could not suppress (see Fig. 59) three point intervals that may have fallen in line by statistical accident. Figures 57 through 60 show examples of this method. The most striking feature of these results is the picking of break points in zones of prominent noise. This same feature was attempted with some difficulty in STEARNS. Good break points are indicated by picks that were all close to the intersection point of adjacent velocity lines and were consistent with eyeball picks. The limitation of this method is in the small number of data pick selections it will make, but it is stronger in its statistical selection of the correct intervals. More work on this method is certain to yield a better solution to data fitting.

Thirdly, radial, vertical, and horizontal geophone data should be averaged and analyzed together for break points.

EXPERIMENTAL SEISMIC SOURCES

Hydraulic Seismic Sources

Introduction

There are several systems available to generate seismic waves using hydraulic or electromagnetically activated transducers: General Atomic, Vibroseis, etc. Advantages of this approach include better control of wave-form and/or frequency-phase characteristics of the propagated signal, and the ability to drive an array of transmitters with identical signals and suitable delays to achieve concentration of energy into a beam aimed in a chosen direction. We have tested the General

Fig. 56. Sample of a hand-fit made by R. T. Stearns.

Fig. 57. 95%-confidence-level fit (sample 1).

Atomic system at the Nevada Test Site, primarily in the shear mode.

Description of Experiment

General Atomic used two vibrating generators of very similar design.³² One vibrated vertically in a shallow pool of drilling mud to produce P-waves; the other, in a trench, vibrated horizontally to produce S-waves. (The latter made P-waves, too.) Another source, described

in GA-6264 and requiring a 7-in.-diam anchor hole, was not used because the unit could not achieve a satisfactory anchor in the hole. Each generator was pulsed at 30 different frequencies for each depth; the signals were summed to produce a sort of cross-correlation function (called a signature). Frequencies used were from 50 to 150 Hz, averaging about 100 Hz. The tool was also used in a single frequency "stacked" mode.

Fig. 58. 95%-confidence-level fit (sample 2).

This "signature" was observed at a surface geophone and a three-component downhole lock-in geophone. The signal sources were from 13 to 18 ft from the top of the hole. The geophones (except for the vertical) were not oriented in space.

System Fielding Characteristics

The process was very slow; this was the first time the S-wave generator had ever been fielded and General Atomic was not really set up to use two generators at once. With breakdowns, each uphole survey took a week. On the other hand, unlike the situation with normal surveys, machinery could run and vehicles could pass while the survey was in

progress and, of course, no HE was used.

Field support requirements for the system were as follows:

- (1) A 5-ft-diam level area with 6-in. dikes to hold a shallow pool of drilling mud.
- (2) A trench 4 ft long, 4 ft deep, and 30 in. wide at a distance of 15 ft from the hole to be surveyed. This trench is for the emplacement of the shear-wave generator.

Results

In theory, the result of summing the signals at the 30 different frequencies is a "signature" (as in Fig. 61(a)) resembling a Ricker wavelet.³³ In practice,

Fig. 59. 95%-confidence-level fit (sample 3).

however, dispersion and multiple-path interference changes the phase of some frequencies, and instead of the single, prominent central spike, we obtain a signal in which two or three central peaks appear equally prominent (see Fig. 61(b)). This in turn forces one to make three "picks" of each signal, hoping that the correct ones will line up and support one another on a depth-time plot (see above). Such a plot is shown as Fig. 62. The result is still somewhat ambiguous. If one considers any one set, a three-layer model of the region results. It is, however, fortuitous that the anomalous layer results in a time shift of exactly one period of the signal. If, one assumes that the proper peak is somehow "lost" in the depth inter-

val 320-380 ft, a single layer model is possible.

A signature results when a group of sine-wave signals of different frequencies are added together in such a manner that all the signals have a positive (or negative) half cycle centered on what is to be the central prominent peak. (See Fig. 63.) The width of the central peak of the signature is approximately the width of a half cycle at the highest frequency present. Inserting a different delay for each frequency and summing gives the ambiguous signature observed in practice. The raw (unsummed) data therefore contain information on the dispersive qualities of the medium. Perhaps a more sophisticated data-reduction

Fig. 60. 95%-confidence-level fit (sample 4).

Fig. 61. "Signature" of summed single frequencies: (a) idealized, (b) real.

system could be used to retrieve this information. Figure 67 shows some results.

The "Swinger" Seismic Source

Some success has been reported on the use of a heavy swinging weight, horizon-

tally striking a target fixed to the earth, as a source of shear waves.³⁴ Our success in applying this method has so far been only fair. A photograph of the apparatus appears in Fig. 64.

Method

In general, the swinger motion has been normal to a radius from the hole to be surveyed (about 5 m away). The shear waves that are recorded travel toward the borehole and down, with particle motion in the horizontal plane, normal to the direction of propagation. The target is a 1 m square of stout angle and channel

Fig. 62. A depth-time plot from "signatures" of summed single frequencies (hole UE-1F, compressional waves).

iron, with a 1.2-cm steel plate welded on one edge as the striking face, which we line with a 1.2-cm lead sheet to reduce ringing and recoil of the pendulum. The pieces of angle iron on the bottom are angled so as to tend to dig into the ground, and there are a number of holes drilled vertically through the target so it can be staked down. Methods of emplacement have involved staking, loading with large weights (such as one wheel of a truck), and burial with a trench cut along the path of the pendulum.

Results

So far, no combination of the above emplacement methods has generated shear waves without serious compressional-wave interference. One method of minimizing this problem is by reversing the direction of swing of the pendulum. This reverses the sign of the shear wave, but not the compressional wave. The traces from each pair of swings are overplotted and times are picked by observing the first significant reversal, seen as a crossing or divergence, of signals on the horizontal geophones (Fig. 65 is an example from recent work). Reversing the detectors in the hole, although theoretically producing the same result, does not work well, perhaps due to mode conversion at the bore-hole wall. In Fig. 66, the results are shown of an experiment in the same hole surveyed by the General Atomic system described above (Fig. 67 shows the General Atomic results). Note that a different time is produced when the swinger is reversed. This is probably due to the target shifting or a different relationship to the zero-time geophone, placed near the target.

The swinger result of 6300 to 6800 ft/sec for compressional waves agrees with the 6600 ft/sec single-layer interpretation of the General Atomic data.

The swinger shear-wave value is 3400 ft/sec. The General Atomic shear-wave data are somewhat ambiguous, giving single-layer values of 2700 to 3300 ft/sec and a two-layer interpretation of 2400 and 3000 ft/sec.

A later swinger survey in another hole, with a readily reversible swinger and more data, is shown in Fig. 68.

Fig. 63. Time compression by frequency summation.

Work in Progress

More experimentation in the type of target and its manner of emplacement is indicated. The purpose is to reduce the ratio of compressive wave amplitude to shear wave amplitude. We have tested a target bolted to a large sheet of aluminum coupled to the ground by friction. The normal load providing the frictional force consisted of large bags of water, elastically decoupled from the sheet so as not to reduce its motion.

A survey in alluvium using this technique gave good signals to at least a depth

of 321 m (the bottom of the hole). Field examination of the data (see Fig. 65) indicates that while a large P component is still present, a phase shift in the later part of the wave can be observed, and thereby a shear arrival determined, to the full depth. A preliminary value of the shear velocity, 762 m/sec, is consistent with the 1200-1600 m/sec compressional velocities measured by an uphole survey.

Other work indicates that sharper, clearer signals are obtainable by using recoil from a gun. We have no plans to try this in the near future.³⁵

Fig. 64. "Swinger" seismic source.

Fig. 65. Sample of "swinger" signals showing crossover.

THE DRY HOLE ACOUSTIC LOG

Introduction

There is a need to obtain velocity information, both compressional and transverse, in dry holes ranging in diameter from 1 to 4 m. None of the currently available methods work. Logging tools require fluid and usually need smaller holes. Uphole surveys cannot be stemmed,

since the holes won't hold water and sand would have to be cleaned out, and, besides, the hole diameter would introduce large distance uncertainties in the stemming. (There is also the expense of transporting the large volume of stemming required.) A large lock-in geophone might be feasible, since the side of the hole on which the geophone was located would not be important at depth, but the fact that the signal might

Fig. 66. "Swinger" data in hole UE-1f.

have to travel around the hole could cause problems. The geophone could be oriented, of course, at a cost of considerably increased tool complexity.

Accordingly, it was decided to build a device to measure microscopic scale velocities, in contrast to the macroscopic scale techniques discussed above. Many

Fig. 67. Shear wave vibrator data in UE-1f.

commercial devices to do this exist, all of which require liquid in the hole as a transmission medium. A source in one part of the sonde emits a pulse that is transmitted through the fluid to the bore-hole wall, through the rock to a point near the detector (or detectors), and then back through the fluid to the detector. (This assumes the velocity in the medium to be greater than that in the fluid—often not the case for shear waves.) For dry holes,

attempts have been made using sources and detectors in liquid-filled bags that were pressed against the wall. These tended to work on concrete floors and to fail in holes. We decided to couple the signal to the walls through acoustic horns.

Preliminary Tests

We first made tests in concrete, rock, and trees, with some simple horns attached to a 25-kHz commercial flaw

Fig. 68. "Swinger" data in hole UE-20u No. 3.

detector, which had small source and detector crystals. These were promising.

We considered both piezoelectric and magnetostrictive transducers, and chose

the former on the basis of availability. From the International Transducer Corporation we obtained transducers, Model ITC-150A, consisting of a stack of 20 each PZT-4 ferroelectric disks, a tailmass, a headmass, and a horn, all designed for 10 kHz. The horn was 38 cm long. These indeed provided resonance at 10 kHz. The output energy was many times that of the flaw detector.

However, we really wanted a pulsed source, for which resonance was not important, and besides, the mismatch between horn and medium destroys the resonance. Therefore, after the first tests with the large horns, we started to reduce the horn size. This both improved the signal and made the eventual sonde smaller in diameter, a very desirable situation. The final horn was approximately 3.5 cm long and, after having reduced the tailmass as well, the transducer with horn was finally 13 cm long (see Fig. 69).

Figure 70 shows the pulser used in the surface tests of these transducers, and Fig. 71 shows the circuit now in use. The source transducer was tested to 2 kV before delivery, and this is the maximum voltage pulse used.

Surface tests in rock and dirt, and later in asphalt and alluvium, with the short horns and reduced tailmass were quite successful, and it appeared that both compressional and transverse waves were observed.

The Sonde

A sonde was built with the transducers 0.914 m (3 ft) apart and clamped in a manner almost identical to the RIDS clamping. A hydraulic pump activates a cylinder,

which opens an arm. The arm can open to 195 cm and clamp for most of this distance. The trunnion mount is identical to that on the RIDS. Figure 72 shows the arrangement. The sonde is 18 cm in diameter and 244 cm long.

Acoustic isolation of the detector from the source was the most difficult problem. Figure 69 shows the current technique, which seems to work quite well. Electronic noise is currently still somewhat of a problem, but is slowly being eliminated.

Tests

The first downhole test of the finished sonde was in a hole in fractured quartzite. The hole was badly washed out from its 0.3-m diameter, and in some places no recognizable signals were obtainable; results were fair to good elsewhere. Compressional velocity could be measured, but the test was incomplete as to transverse waves. This hole had previously been filled with mud and logged with a conventional tool (Birdwell 3-D). Signals were very weak even with fluid coupling, but agreement was not bad.

Tests in 1.2-m and 1.5-m holes in alluvium were quite successful. Figure 73 shows several signals from these tests and Figs. 74 and 75 show plots of velocity vs depth in two cases.

Recently we were able to compare data from the dry hole acoustic log (DHAL) to those from an uphole survey in the same hole (which was very rough). A computer program, EREBOR, was written to reduce the data from the oscilloscope records of the DHAL and plot as a function of depth, velocity and integrated time (determined by averaging the time for two records and

Fig. 69. Design of the transducer mounting for the dry hole acoustic log.

assuming a velocity appropriate to this time between recording depths). A plot from EREBOR is shown in Fig. 76, with the uphole survey data hand-plotted on it. The lines drawn on the uphole data have the same slope as the sections of the DHAL record at the same depth.

There are disagreements as great as 12% between the two sets of data. However, it was often difficult to find the first

arrival on the DHAL records. A signal averager could be used to improve this situation greatly. It should be noted that the DHAL always shows average velocities smaller than or equal to those from the uphole. This is consistent with missing the first arrival and could presumably be corrected with a signal averager.

A computer program has been written that displays simulated digitized DHAL

Fig. 70. Circuitry for the DHAL pulse generator.

Fig. 71. Circuitry for the DHAL preamplifier.

Fig. 72. Dry-hole Acoustic Log sonde.

450 to 500 ft

500 to 550 ft

550 to 600 ft

650 to 700 ft

Fig. 73. Sample signals from the DHAL in a large hole in alluvium (sweep rate = 0.2 msec/cm) showing repeatability. Traces 10 ft apart in depth.

data in the manner of a "3-D" log display. It uses the DD80 "shader" routine and the film, if printed slightly out of focus, seems to make a nice "3-D" (or variable intensity recorded sonic log) display. A sample is shown in Fig. 77. If a signal averager and digital tape were available, such plots could be made from field DHAL data.

The input for EREBOR is shown in Table 4.

This system is designed for a picture with several records on it, each for a different depth. Each "reading" identified by dial 9 requires reading of two points on the microscope. There is a modification available if two oscilloscopes are used for each signal, and only the second arrival is on the second oscilloscope. If the code sees a 0 in dial 9, indicating a baseline, and then a 2, it knows that there is no

Fig. 74. Data from the DHAL in a large hole in alluvium.

Fig. 75. Data from the DHAL in a large hole in alluvium.

Fig. 76. DHAL data compared to an uphole survey in alluvium.

first arrival, and it will interpret the second point read as a second arrival. This makes it possible to read both compressional and shear waves on either one or two oscilloscope records.

A special board is required in the card punch to prepare input for this code—it is currently on the shelf next to the micro-

scope interpreter. It prepares cards as follows (where a number is the number in a dial, X a digit of the X axis, and Y a digit of the Y axis):

```
123459XXXXXXXXXXXXXXXXXXXX
123459XXXXXXXXXXXXXXXXXXXX
123459XXXXXXXXXXXXXXXXXXXX67.
```

Fig. 77. Mockup of DHAL used as a "3-D" log on the computer.

Table 4. Input for EREBOR—dry hole acoustic log data reduction code.

Card	Column	Information
1	1-40	Title
	41-50	Time, in msec, for a signal to travel from source to detector with transducer horns touching each other.
	51-60	Digitized microscope units per oscilloscope centimeter.
	61-63	If reading times instead of distances on an oscilloscope, the number of times read.
2	1-10	ft/inch on Calcomp plot.

The remainder of the cards are produced by our digitized microscope, which has electronics including nine dials. Dial settings indicate necessary information as follows:

Dial	Value	Meaning
1-5		Depth in ft, with dial 5 reading fractions.
6-7		Sweep speed of last film read on card, in hundredths of a msec per cm, e.g., if dial 6 reads 2 and dial 7 reads 5, sweep is 0.25 msec/cm.
8		Unused.
9		Used to indicate what is being read on microscope.
9	0	Baseline (first two points read on a film, to compensate for film tilt).
9	1	A first arrival (a pair of points, zero time and the arrival on a sweep).
9	2	A second arrival, being the first of a pair of readings.
9	3	Second and third arrivals.
9	4	Reading is finished.

Water Content

A STUDY OF NEUTRON LOGGING

Water content is generally measured either by electric logs or neutron logs. The use of electric logs involves so many assumptions about the medium that, while often valid in oilfield rock, do not work at NTS, that we have never used such logs (see the section on "Electric Logs").

The standard method of measuring water or hydrogen content using neutrons has been to count thermal neutrons, usually from a radioactive source, or to measure gamma rays produced by thermal neutrons.^{36,37} More recently, counting of epithermal neutrons has been favored,³⁸ and the theory of epithermal-neutron logging has been treated analytically and extensively.^{39,40} Many Soviet authors have studied the problem.⁴¹ More sophisticated methods have also been used, including the measurement of the lifetime of thermal neutrons in a medium.⁴² Recently Caldwell et al. proposed using the lifetime of epithermal neutrons as a measure of hydrogen content,⁴³ and even more recently the same group proposed using the ratio of counts in two thermal detectors to measure the water content by diffusion of epithermal neutrons.⁴⁴

While Tittle has given the analytical solutions for both the ratio method and the single detector method, no study has been made of the effects of washouts, reactor poisons, and holes, or, for that matter, of significant variations in the chemistry or density of the medium. The work reported here tested the epithermal-

lifetime method, the single-detector epithermal methods, and the ratio method in a rather unrealistic geometry, but with large variations in all the perturbations discussed above.

Formulation of the Problem

Monte Carlo calculations are probably the best way of examining the effects of perturbations on epithermal neutrons since one can easily vary the geometry, the chemistry, and the source-detector distance. Monte Carlo calculations have been made for the neutron log,⁴⁵ but no significant variation in the hydrogen content was made, nor were any perturbations inserted. The SORS code is useful for such variations.⁴⁶ One can use any geometry expressible by conic sections, a neutron source of any desired energy, any desired combination of 50 different isotopes at any desired density, and any desired angular distribution at the neutron source. Depending on the nuclide and the neutron energy involved, collisions may be either isotropic or anisotropic in the center-of-mass system and may be elastic, inelastic from a single level, or statistical-model inelastic. A table of cross sections and relative probabilities for the various kinds of collisions is included in the code. Each zone of the problem can be assigned a statistical weight. When particles cross a boundary to a zone of higher importance (lower weight), each is split into two particles. When the particles go in the opposite direction, half of them are eliminated. The ratio of the weights of adjacent zones may be two, one, or one-half.

The first problems run were in a cylindrical geometry, a very good approximation to borehole conditions. A borehole with a 6.5-cm radius was surrounded by hollow cylindrical detectors 1 cm thick. These were in turn surrounded by a medium with a 100-cm radius. The cylinder

The time required to run a problem can be reduced by a factor of three by changing to the disk geometry shown in Fig. 78. If the problems in the disk geometry tend to fit the same functions as those in the cylindrical geometry, one may conclude that the change is acceptable as an approximation to borehole conditions.

Fig. 78. Geometry of the disk-shaped problem showing zone numbers, weights, and positions of the detectors. The detectors are 10 cm wide, 1 cm thick, and 10 cm apart, detector 1 is 20 cm from the source. The medium is 54 cm thick and 70 cm in radius. The borehole is 5 cm thick.

especially since, in any case, conclusions must be confirmed by experiment. Disk and cylinder problems do tend to fit the same functions at a density of 1.0 g/cm^3 (see Figs. 79 and 81); no cylinder problems were run at higher density, since machine time increased with density. It should be noted that the disk is a good approximation to a very large borehole.

The weights shown in Fig. 78 were chosen so that the neutrons were driven from the source to the outer edge of the disk toward the detector farthest from the source. In this manner, a certain amount of realism is lost, but efficiency is gained. A pulsed 14-MeV source with 10^5 neutrons was used, and the angular distribution was conical, so that no neutrons could enter the detectors directly, and none could go directly into the void below the borehole. The angular distribution was isotropic in a 60-deg angle about the axis of symmetry. Three detectors were located at the edge of the medium to simulate eccentric and totally absorbing detectors in a borehole.

There are zones representing the borehole that can be filled with air, water, or whatever is desired. The zone numbers in Fig. 78 will be referred to when describing the problems. Each problem took from 45 to 90 min on a Control Data Corporation 3600 computer. In order to investigate errors, two problems in which the count rates in the outermost detector were quite low were repeated. The spread was 26% in the worst case; error was generally less than 5%.

The perturbations used were various "poisons" in concentrations much larger

than could be expected in any rock medium,⁴⁷ washouts in zones 14 and 17 and water in zone 19, and three different medium chemistries—pure oxygen, pure aluminum, and pure SiO_2 , each containing the hydrogen admixture. In the "borehole," air, fresh water, and water with 5 at.% chlorine were used. When the SiO_2 was used, a grain density of 2.85 g/cm^3 was assumed (this is unrealistically high, but does not affect results, and the bulk density was altered to fit 5, 20, and 35% water-filled porosity).

Results

The epithermal-neutron flux (summed from 0.3 to 1300 eV) was never found to be a monotonic function of hydrogen content for a bulk density of 1.0 g/cm^3 . Therefore, attempts were made to fit some function of density and hydrogen content to the results.

It has been shown from age theory in many places⁴⁸ that the epithermal-neutron flux (ϕ) at a given radius is

$$\phi(r, L) = \frac{C}{D} \frac{e^{-r/L}}{r}, \quad (36)$$

where r is the distance from the source, L is the slowing-down length, D is the diffusion length, and C is a constant that depends on source strength. This equation holds in a homogeneous, isotropic medium with an isotropic single-energy source for a one-group calculation. Let us make the dubious assumption that this expression holds in the disk case calculated here. For the slowing-down length, Kozhevnikov⁴⁹ gives

$$L^2 = \tau_S(u) = \overline{\lambda^2}(u) \left\{ \frac{\nu_0^2}{3} + \frac{u}{3\xi(1 - \overline{\cos \theta})} + \frac{1 - \xi_0}{3\xi(1 - \overline{\cos \theta})} + \frac{\nu_0 \overline{\cos \theta}_0}{3(1 - \overline{\cos \theta})} - \frac{5 \overline{\cos \theta}}{9\xi(1 - \overline{\cos \theta})^2} + \frac{1}{3\xi(1 - \overline{\cos \theta})^2} \right\}, \quad (37)$$

where $\overline{\lambda^2}(u)$ is the mean square of the mean free path in the slowing-down range $(0, u)$, $\overline{\cos \theta}$ is the mean cosine of the scattering angle, and ξ is the mean change in the lethargy for a single scatter. In this equation, ξ_0 and λ_0 are similar functions at the initial neutron energy, and $\nu_0^2 = \lambda_0^2/\lambda^2(u)$.

Since λ is proportional to $1/\rho$ (where ρ is bulk density), and since ξ and $\overline{\cos \theta}$ are functions of the hydrogen content, let us make the extremely simplifying assumption that

$$D \propto L \propto \frac{1}{\rho n_h}, \quad (38)$$

where n_h = moles of hydrogen per cubic centimeter. If all the hydrogen is assumed to be in water-filled pores, the percent porosity = $900 n_h$. Then, at a given radius

$$\phi(r, L) = C \rho n_h e^{-K \rho n_h}, \quad (39)$$

where C and K are various constants (functions of radius, source strength, etc.).

The number of epithermal neutrons detected in each detector was compared to Eq. (39). Figure 79 shows the best set (detector 2) with air in the borehole. A

straight line is a fairly good fit with the constant chemistry of oxygen, but chemical effects are fairly large. SiO_2 and aluminum are not very close to the curve. (Of course, in the field gross chemistry would be known, and furthermore most minerals have from 40 to 70 at.% oxygen and are therefore fairly similar.) The cylinder data are not a bad fit to a straight line.

When water was put in the borehole, the fit was bad. It was therefore assumed that the medium provided only half the density effect and that the expression for L should be

$$D = L = \frac{1}{0.5 C n_h (1 + \rho)}. \quad (40)$$

Thus,

$$\phi(r, L) = 0.5 C n_h (1 + \rho) e^{-0.5 K n_h (1 + \rho)}. \quad (41)$$

With this assumption, quite a good fit was obtained with water in the borehole and with n_h between 0.01 and 0.05. Figure 80 shows the best such fit, again at detector 2. The relative success of these fits gives some credence to the assumptions in Eqs. (38) and (40) and encourages proceeding to the ratio method.

Allen et al. proposed using the ratio of counts in two detectors as a good method of measuring water content.⁴⁵ No fit of any sort could be made in this work with a ratio of two detectors; such ratios were either too sensitive to perturbations or not sensitive enough to hydrogen. Using three detectors is unsatisfactory since the advantage of the ratio—the fact that only the exponent is a function of L —does not obtain. We therefore tried

Fig. 79. Fit of $\phi_2 = C \rho n_h e^{-K \rho n_h}$ with air in the borehole.

$$Q = \frac{\phi_3^2}{\phi_2 \phi_1} = K \frac{e^{-2f_3(r,L)}}{e^{-f_1(r,L)} e^{-f_2(r,L)}} = K e^{-C \rho n_h} \quad (42)$$

for air in the borehole, and

$$Q = \frac{\phi_3^2}{\phi_2 \phi_1} = K e^{-0.5 C n_h (1+\rho)} \quad (43)$$

for water in the borehole.

When these "fits" were plotted directly, no good straight line was found. A fit to $Q = \phi_3 \phi_2 / \phi_1^2$ was not significantly better. However, when the equations were rearranged and

$$Q^{1/\rho} = e^{-C n_h} \quad (44)$$

was tried for air (see Fig. 81) and

$$Q^{2/(1+\rho)} = e^{-C n_h} \quad (45)$$

was tried for water (see Fig. 82), a smooth curve, fairly linear to $n_h = 0.03$, could be drawn through the air data with errors in n_h no worse than 30% up to $n_h = 0.05$. The fit was not as good through the water data. Cylinder data are a good fit to a straight line.

Chemical effects are somewhat less severe, especially in the SiO₂ case, when the ratio method is used.

Fig. 80. Fit of $\phi_2 = 0.5 C n_h (1 + \rho) e^{-0.5 K n_h (1 + \rho)}$ with water in the borehole.

Epithermal lifetime was also studied. Neutrons in the detectors were counted in the time intervals 0 to 5, 5 to 10, 10 to 20, 20 to 35, and 35 to 50 μsec after the pulse of 14-MeV neutrons (which itself took zero time). The number of neutrons in each interval was divided by $T/5$ (where T was the time interval), and a smooth curve was fitted. The lifetime was then taken to be the time required for the counts in detector 2 to decrease to one tenth of that in the first time interval. The results, with air in the borehole, of plotting lifetime vs n_h are shown in Fig. 83. There is a great deal of scatter

The assumptions made in Eqs. (38) through (41) are valid only insofar as they are successful in fitting the results. Kozhevnikov⁵⁰ shows that L becomes almost a constant at an n_h greater than about 0.04. Thus, straight-line fits should not be expected to be good beyond that value. Fits below an n_h of 0.005 are discussed below. Between these values, a straight line seems to be a good fit to a single detector. Cylinder problems tend to confirm this result, but may (see Fig. 79) show the beginning of levelling of L at $n_h = 0.03$.

Fig. 81. Attempted fit of $(\phi_3^2/\phi_2\phi_1)^{1/\rho} = Ce^{-Kn_h}$ with air in the borehole.

Ratios are less satisfactory in the flat-geometry calculations, even though they reduce medium-chemistry effects. However, the cylinder results indicate that the ratio method may, in reality, be best. The scatter may be partly due to the sensitivity of the ratio method to the flux in detector 3, which scatters greatly. If a tool were to be built utilizing the ratio method, it should contain four detectors (two on each side of the source) at distances corresponding to detectors 1 and 2.

The fair fit of the results of the cylinder problems to Eq. (39) and the good fit to Eq. (44) tend to confirm the reality of the results of the disk problems. It

is not, of course, to be expected that the same lines will be fitted, since detector sizes are quite different in the two geometries. It is interesting to note that the cylinder problems indicate that the ratio method is more sensitive to η_h than the single detector method.

Two problems were examined to test the fit of

$$\phi = \frac{Ce^{-Kn}}{r} \quad (46)$$

for constant L , which fit should be good if the assumptions are valid. In the cylindrical problem, such a fit was good. In the disk geometry, zones 1, 2, 3, 5, and 6 were all used as detectors in one

Fig. 82. Attempted fit of $(\phi_3^2/\phi_1\phi_2)^{2/(\rho+1)} = Ce^{-Kn_h}$ with water in the borehole.

problem, and a straight-line fit was successfully made to all but detector 1, which apparently was too close to the source.

Caldwell et al. used rings of detectors in a cylindrical geometry and varied the effect of slowing-down length by varying the neutron energy rather than the hydrogen content.⁵⁰ They appear to have found that the ratio of count rates in two of the ring detectors was proportional to $e^{-1/L}$.

Ølgaard found, among other things, that the derivative of the count rate in a counter with respect to the density was a linear function of the porosity.⁵¹ He used thermal rather than epithermal neutrons,

and his geometry was such that none of our detectors approximates it. However, by looking at the count rate in zone 8 (closest to the source), one can make some sort of comparison. It is found that the derivative of this count rate with respect to density is indeed a linear function of the porosity (see Fig. 84). Ølgaard used densities varying between 1 and 1.8 g/cm^3 . The problems that were studied in this case had densities of 1 and 2 g/cm^3 and "porosities" of 3, 9.9, and 29.2%.

Tittman et al. have performed a series of experiments with their sidewall

Fig. 83. Lifetime with air in the borehole (detector 2).

epithermal-neutron porosity log and have shown plots of count rate vs porosity for air- and water-filled holes.³⁹ An attempt was made to fit their data to Eqs. (39) and (41). Figures 85 and 86 show those fits. It can be seen that the fit is quite good except at very low porosities; however, it must be recognized that the density variation in their work is very small, and that a straight line can be fitted to their data on count rate vs porosity in this range. Consequently, the only real evidence for the validity of the present work that could be obtained would be negative, and, indeed, at an n_h of 0.005 there is a severe disagreement. In their work,

the count rate at this low porosity is much higher than that at higher porosities, whereas in this present work, the count rate at the low porosity is much lower. This latter effect obtains even in a problem with cylindrical geometry. There are several possible explanations. One is that our problem is of finite size, whereas Tittman's experiment is effectively infinite in size. Another is the difference in effective source-to-detector distance. It appears that their source-to-detector distance is about 60 cm. However, their neutron source is either plutonium-beryllium or americium-beryllium, whereas in our

Fig. 84. Plot of $d\phi/d\rho$ vs porosity ($9 \times n_h$). Compare with Olgaard.

problems the neutron energy was 14 MeV. Therefore, the effective source-to-detector distance in our problems is substantially less.

One can only conclude from the comparison with Tittman's data that the calculation below an n_h of 0.01 should be viewed with suspicion until it is confirmed experimentally. It should, however, be noted that in the case of water, the use of Eq. (41) almost eliminated the chemical effects seen by Tittman.

In general, it appears that the method of measuring hydrogen content with a single detector and fitting to Eqs. (39) and (41) will probably be usable provided some medium-chemistry correction is made. The ratio method with four detectors is also promising. It is clear, of course, that laboratory tests must be

performed before such methods can be used in the field. Preliminary design of a suitable test facility with density varying between 3.0 and 1.0 g/cm³ at $n_h = 0$, and between 2.5 and 1.0 g/cm³ at $n_h = 0.04$, with intermediate values in between, has been completed. It is hoped that we can construct such a facility and use it to test both commercial tools and the ratio method over this density and hydrogen content range.

A NEUTRON LOG CORRECTION CODE

The discussion above is theoretical. While a test facility has not yet been built, it has been possible to try an epithermal neutron log in a hole below the water table, and compare it to water contents obtained from samples of the material. Schlumberger runs an epithermal neutron log which has at the top three scales (see Fig. 87) for porosity, labeled "Limestone," "Sand" and "Dolomite." Since NTS rock is rarely and of these, we thought it would be a good idea to try to correct the data.

For a log whose output is in porosity, with a built-in density assumption (such as the grain density of limestone plus the appropriate amount of water), Eq. (39) reduces to $\rho_1 P_1 = \rho_2 P_2$, where the subscript 1 refers to the assumed material, 2 refers to the true material, and P is volume porosity. ρ_1 is computed for the assumed material, and ρ_2 is taken from a log.

The formula was tested by comparing the three scales on the Schlumberger log. For sand and dolomite, the porosity from the appropriate scale was compared to the porosity that would have been obtained if the material were assumed to be limestone.

Fig. 85. Data of Tittman et al. (1965) plotted in the form of ϕ/ρ_h vs ρ_h with air in the borehole.

The true density was computed for the porosity, and the correction was made. Results are shown in Fig. 88. The correction is very small for sand and fairly effective for dolomite. It can be seen from Fig. 88 that the sand data are displaced; this is probably due to a chemical effect. The same data are shown in Fig. 89, with the percentage of error shown. Of course, a small absolute error is a large percentage at low porosity.

Since the density correction is not too effective for sand, it was decided to make a chemical correction as well. Porosity was arbitrarily added to the limestone

values to place the value approximately halfway between dolomite and sand values, and then the density correction was made. The results, in percentage terms, are shown in Fig. 90. Dolomite values are no longer improved, except that corrected values are better than raw values at high porosity, since the arbitrary addition and the density correction work in opposite directions. Sand results are greatly improved and, of course, limestone results are no longer perfect. Since most of the NTS rocks we work with tend to be silicates, this correction seems to be more satisfactory than a simple density correction.

Fig. 86. Data plotted as ϕ / ρ_h vs ρ_h with water in the borehole (Tittman et al.).

A code, ANDUIN, was then written. As input it takes Grafacon (RAND tablet) readings of the porosity and density logs

normally of the limestone scale on porosity, and output is in the form of Cal-comp plots of raw data, density corrected

Fig. 87. Sample sidewall epithermal neutron log.

Fig. 88. Epithermal neutron-log calibration data corrected for density only.

data, and density plus chemistry corrected data. (See Table 5 for the ANDUIN inputs.) A log is shown in Fig. 91.

Also plotted on Fig. 91 are porosities computed by Art Lewis from core and

cutting data.⁵² Core results differ violently from cutting results. Cutting results are in pretty good agreement with the log. It would be expected that cutting results would be low, especially in the

Fig. 89. Percent error in neutron-log calibration data corrected for density only.

region above 2950 ft and below 3250 ft, where the material is rhyolite. It is not evident from this log that the corrected results are any better than the raw data. Corrections are small, and the error in the cutting data is probably greater than the corrections to the log. No conclusion can be reached from this log as to the value of the corrections.

The log was run below the water table. From Tittman et al. (above) it appears that the chemical correction should not be used above the water table.

A hole was drilled with vacuum above the water table in alluvium. Cuttings from the hole were sampled every 10 ft. A portion of the sample was sieved, and the larger pieces were put in an aluminum

Fig. 90. Percent error in neutron-log calibration data corrected for density and "chemistry."

can, which was sealed at the hole with an old-fashioned home canning machine. An unsieved sample was also canned. Water content of these samples was measured by weighing the can, punching a hole in it, baking it at 110°C, and then weighing again.⁵³ Can weight was

of course subtracted, and the can was designed so as not to cause problems. Since passage up the hole might dry out the samples, a piece of core was sacrificed and tested; it agrees well with the cuttings samples. A few samples were also heated to 1050°C to test for bound water.

Table 5. Inputs for ANDUIN.

Card ^a	Column	Meaning
1	1-50	Title
	51	If positive, correction for chemistry is not made. This should be used for dry holes.
	61-70	Ft/inch on Calcomp plot.

^aThe next cards carry output of the neutron log, as read on the Grafacon in Nevada, using the limestone scale on the log. The first five fields on each card are depths, and the second five are for nominal porosity corresponding to those depths. When the code encounters a blank depth field, it looks for a new set of cards of the same format, but carrying depth vs density. Another blank field signals the end of the input.

A logging company has recently published a technique for correction for an "excavation effect," or the effect of densities lower than those for saturated materials. Figure 92 compares the logger's data, both measured and corrected for various densities with Eq. (39). As can be seen, agreement is good down to $\rho n_h = 0.04$, which is equivalent to 15% porosity in saturated limestone. Figure 93 compares corrected values for various measured densities using the logger's method and $\rho_1 P_1 = \rho_2 P_2$. Agreement is reasonably good. Therefore, we may assume that ANDUIN results are essentially equivalent to the logger's excavation correction.

Figure 94 is a comparison of the neutron log in the hole and the cuttings data. The dotted line on the log is the raw data, in terms of limestone porosity, and the dashed line is the data corrected for density by ANDUIN. The wt% water is

simply the vol% divided by the density. LRL densities were used.

The short horizontal lines are the cuttings results, where the cuttings were taken from sections of the hole as shown. The one result from core, and three measured at 1000°C are also shown. A fourth at 1000°C from below the bottom of the log also agrees well with the 110°C data. Where two values are shown at the same depth, one (generally the higher) is from the sieved sample, and the other is from the bulk sample. Where only one is shown, it is from the sieved sample.

Clearly, agreement is very bad, but there is a possible explanation. Figure 95 shows the logger's data plotted as l vs ρn_h and the values that would be obtained if Eq. (39) were fitted to the straight line of Fig. 92. Two points should be noted:

- (1) The double-valued curve was not used in the correction.
- (2) The data used for this fit are not from the logging tool used in the measurement.

Now, as can be seen, the curve represented by Eq. (39) turns over, whereas the logger's data do not. Physically, it is nonsense for l to go to zero when n_h goes to zero, since the medium, even without water, must scatter neutrons, and so the logger's data (which, it must be remembered, are measurements) are perfectly reasonable. However, it is physically necessary for l to go to zero when ρ goes to zero, and therefore we must realize that in some situations turnover must indeed occur.

If an average value of, say, 25% limestone porosity is chosen from the log raw data, and ρn_h in Fig. 95 is given this

Fig. 91(a) through 91(g). Sample LRL corrected neutron log in wet hole. Dotted line represents raw data for the limestone scale; dashed line is for density correction only; solid line is for density and chemistry corrections.

Fig. 91(b)

Fig. 91(c)

Fig. 91(d)

Fig. 91(c)

Fig. 91(f)

Fig. 91(g)

Fig. 92. Comparison of logger's excavation correction to Eq. (39) — dry hole. Each point at a given porosity represents a density decrease of 0.5 g/cm^3 from "nominal."

value, the value of ρn_h on the other branch is about 0.014. With ρ about 1.6, n_h is then about 0.00875. This yields 7.9% water by volume, which would be about 5%

by weight, and this is lower than most of the measured values. Further, if the calculated curve in Fig. 95 actually represents nature, and we are on the back

Fig. 93. Comparison of LRL and logger's correction curves.

side of the curve, then the cuttings values would vary inversely with the log data, and this appears not to be the case.

From the arguments above we see the Eq. (39) is not fully satisfied by the real data. Perhaps there is another term that was not obtained from the Monte Carlo calculations. But Eq. (39) appears to be partially correct. Further investigation is obviously required, preferably in unsaturated test wells. We hope some day

to build some. For logging in alluvium, it might be desirable to build an epithermal neutron log designed so that the turnover point, which on the current one is at a nominal density of 15%, could be moved significantly in either direction, since the region of turnover (if it really exists) in the current design is in the region of interest. Perhaps a calibration of the actual logging tool used would help explain the differences also; if it turns over at a

Fig. 94(a)

Fig. 94(b)

Fig. 94(a) through 94(c). Corrected neutron log in unsaturated material compared to cuttings data.

on its back side
data.

be used to
clude microwave
n,⁵⁴ capacitance
uclear magnetic

resonance.⁵⁶ To date, no way of making
these techniques work accurately under
test site borehole conditions has been
devised.

However, we have been in communica-
tion with companies working with both the
microwave and capacitance methods, and
there is some hope that they will produce
a proposal that will result in a useful tool.

Electric Logs

ing the electric
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een developed
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ration is simply
tances. If R_t
e E-log, and
hip concerning
pore space can
Humble formul-
relationship:
la:

$$\text{or: } F = R_o/R_w;$$

or vs porosity,
 $\phi^{2.15};$

on % of pore
ontaminated

stivity

R_{xo} = flushed zone resistivity,
 R_{mf} = mud cake resistivity,
 R_w = ground water resistivity,
 R_o = formation resistivity when
100% saturated,
 ϕ = percent porosity.

When these formulas are applied to
data from NTS, chaos is the usual result.
Although some research has been done in
NTS soils to make these logs more useful
(R. Carrol at the USGS, Denver), three
major problem areas are indicated:

- (1) Input data for the above formulas,
taken from the E-log, are either
uncorrected, uncertain, or un-
known, and in many cases human
judgment is necessary to pick
usable data. This is because re-
sistive transition zones from
horizontal layering gives rise to
anomalies in the response of the
tool. It is very pronounced when
bed thickness is nearly the same
as the electrode spacing. Bore-
hole conditions must be measured
and corrected before true forma-
tion resistivity can be obtained.
Mud resistivities, formation water

Table 6. Schlumberger Well Surveying Corporation log interpretation charts reference sheet

Symbol	Explanation
AM	Normal curve spacing
AO	Lateral curve spacing
BHT	Bottom hole temperature in °F
d	Diameter of the hole
D_1	Average diameter of invaded zone
e	Bed thickness in feet
t_{mc}	Mud cake thickness
R_m	Resistivity of the mud
R_{mf}	Resistivity of the mud filtrate
R_{mc}	Resistivity of the mud cake
R_w	Resistivity of the formation water
R_{wa}	Apparent resistivity of the formation water in shaly sands, or R_t/F_s
R_L	Resistivity of the mixture of the electrolytes (It can be defined for a given zone—invaded or noninvaded)
R_t	Resistivity of the formation—uncontaminated zone
R_o	Resistivity of the formation when 100% water
R_i	Resistivity of the invaded zone
R_{xo}	Resistivity of the flushed zone (close to borehole)
R_s	Resistivity of the surrounding beds
$R_{16"}, R_{64"}, R_{18'8"}, R_{1'"} \times 1' "$ and R_2	Apparent resistivity of 16 in.-normal, 64 in.-normal, 18-ft 8 in.-lateral, 1-in. $\times$ 1-in. microinverse, and 2-in. micronormal, respectively
R_{IL6} or R_{ILd} , R_{IL5} and R_{ILm}	Apparent resistivity of 6FF40, 5FF40, and medium induction, respectively
F	Formation resistivity factor
F_a	Apparent formation resistivity factor
ϕ	Effective porosity in percent
S_w	Water saturation, percent of pore space in uncontaminated zone
S_i	Water saturation, as above, in invaded zone
S_{xo}	Water saturation, as above, in flushed zone
ROS	Residual oil saturation as percent of pore space; $= (1 - S_{xo})$
K	Coefficient in the SP formula
SSP	Static spontaneous potential—the maximum possible for a particular R_{mf}/R_w
PSP	Pseudostatic spontaneous potential—the SP found in a thick shaly sand
α	SP reduction factor— PSP/SSP
k	Permeability in millidarcies
Δt	Sonic transit time in $\mu\text{sec}/\text{ft}$
ρ_B	Bulk density in g/cm^3
SP formulas	$SSP = -K \log_{10} R_{mf}/(R_w)_e$; $PSP = -K \log_{10} R_{mf}/R_{wa}$
Sonic time-average formula	$\Delta t = \frac{\phi}{\sqrt{\text{fluid}}} + \frac{(1 - \phi)}{\sqrt{\text{matrix}}}$
Formation density formula	$\rho_B = \phi \rho_{\text{fluid}} + (1 - \phi) \rho_{\text{grain}}$

It is noted that the constants in these formulas may hold for ideal oil field formations, but they are not well understood for volcanic. These "constants" indicate some information about the cementation of the medium, but they are also a normalization factor which could reflect other unmeasured properties of the formation water.

- (3) The nature of the medium at NTS is such that the presence of the clay matrix causes difficulties. The major problem is that formation water resistivity is dependent on the geometry of the pore space and the natural resistivity of the water it contains. This is due to the fact that the conductance of an electrolytic solution is a function of the motion of relatively large ions in the liquid. The speed of these particles, and consequently the conductivity, is dependent on their mobility, depending on the viscosity of the solution and geometry of the pore space.

The clays and rhyolites at NTS apparently have considerable restraining effect on the motion of large ions. At this time, there are no known analytical or empirical equations to express the interrelation of pore space geometry and the water resistivity. The apparent higher resistance of the formation water causes the Archie and Humble equations to indicate higher saturations and porosities and low formation factors. As formation water resistance approaches the resistance of the formation, both equations become very insensitive to porosity and water content.

The present use of the E-log still remains as a correlating tool. It indicates relative layers of high or low cementation and may indicate the presence of aquifers or zones of large clay content. For this log to be useful in a quantitative way, the following investigation would be necessary:

- (1) The application of formulas to remove anomalies due to layered beds for the larger tool penetrations.
- (2) Calculation of borehole fluid resistivity and its influence on the water resistivity and formation resistivity.
- (3) Correlation with other logs to provide corrections to the E-log, models for cross-correlation, and missing parameters for the Archie and Humble formulas.

At present, only the digitization of E-logs for replotting by computer codes has been accomplished at NTS (see Fig. 97). This is available on request.

For the future, a method of continuously calculating the hole effects such as R_w , R_t , mud thickness, and true formation resistivity is being attempted.

Briefly, this method consists of taking the Wenner configuration of resistivity measurement, which measures the depth (H_1) of resistive beds below the surface (Hummel's principle),^{58,59} and applying this technique to the three-electrode tool. By using three equations and three unknowns, R_w , H_1 , and R_t might be measured continuously. The caliper log would be used as a crosscheck where the diameter of the hole should be within a few inches of depth of penetration (H_1). Although the method needs considerable refining, one trial calculation indicated

Fig. 97. Sample electric logs.

an invasion diameter of 62.7 in., as compared to 52 in. given by the borehole caliper. This shows a mud thickness of approximately 5 in. Fracturing might be indicated if large water-filled fractures

were within the radius of measurement. The comparison to the caliper might result in very large mud wall thicknesses when using the lateral log in conjunction with the 64-in. normal electric log.

Strength, Elastic Properties, and Interstitial Fluid Pressure

PACKERS

Some consideration has been given to direct measurement of elastic properties in place. A device is commercially available for such measurements, but it involves many assumptions and is primarily designed for soil.⁶⁰ A pair of instruments to measure both elastic properties and pore pressure was proposed, but never pursued.⁶¹ One of these instruments consisted of a pair of inflatable packers spaced approximately 5 ft apart, with a third packer filling the space between the first two. This third packer was to contain radial displacement transducers and all three were to contain pressure transducers. The first two packers would seal the hole and the third could be used to measure rigidity modulus by comparing radial displacement or volume change to pressure; by simple monitoring of the pressure buildup after the first two had sealed the hole, the third packer could determine the pore pressure.

The second instrument was to consist of two curved, inflatable packers (see Fig. 98) arranged to bear on opposite quadrants of the hole. These would be hydraulically coupled and equipped with displacement transducers and would establish a second relationship among radial stress, Poisson's ratio, and Young's modulus. By use of the results of both sets of measurements, the elastic constants could be determined.

STRENGTH

We have been unable to propose a suitable method for measuring shear

strength vs confining pressure (the important input to the computer calculations) in place. However, one experiment done on the Schooner Event indicated a possible attack.

The accompanying figures (Figs. 99 through 102) show the variation in seismic amplitude vs depth that resulted from the uphole survey in a hole. The data were obtained as follows:

- (a) The amplitude of the first peak on each seismic record was measured.
- (b) This was converted to volts out of the amplifier and divided by the amplifier gain to obtain input volts proportional to particle velocity in the seismic wave.
- (c) Using velocity-vs-depth data, the "apparent" or "image" depth was calculated for each combination of shot point and geophone station—since the different geophone stations produced somewhat different velocity-vs-depth profiles at the hole.
- (d) The results of (b) were multiplied by $[(d^2 + x^2)/wd]$, where d is the apparent depth, x is the horizontal distance of the geophone station from the hole, and w is the yield of the explosive. This corrects at once for 4π divergence of energy through the different velocity layers, variation in shot strength, and the fact that the geophones are sensitive only to the vertical component of particle velocity. (This relationship of particle velocity to yield is not the one usually used, but it appears to fit the data.)

Fig. 98. Proposed packer for measuring elastic properties of rock in place.

(e) The resulting data were plotted as Figs. 99, 100, and 101.

If one overlays the figures, one obtains excellent agreement between the three detectors for depths greater than 200 ft, with a small amount of normalizing to account for different coupling efficiencies at the three geophone locations. In Fig. 102, the three sets are normalized to the 468-ft point of the west geophone. Included in the figure are the velocity and density data as measured. Note that the low amplitude zone from 250 to 350 ft is bounded by break points in the velocity-

density data but is not in the region of lowest velocity or density.

Several explanations present themselves:

- (1) The coupling efficiency varies with the caliper of the sand-stemmed hole.
- (2) The coupling efficiency varies with the degree of acoustic mismatch between the sand stemming and the formation.
- (3) The coupling efficiency varies with the strength of the medium.

Fig. 99. Corrected seismic amplitude vs depth (east geophone).

Fig. 100. Corrected seismic amplitude vs depth (west geophone).

Fig. 101. Corrected seismic amplitude vs depth (north geophone).

54	53	52	51	SOC material
<1%	5%	20%	3%	Water content
2.4	1.5	1.7	2.2	Density
7000 ft/sec	4000 ft/sec	6500 ft/sec	8800 ft/sec	○ 15 ft West
7000 ft/sec	4300 ft/sec	6700 ft/sec		▲ 15 ft North
7000 ft/sec	4200 ft/sec	5500 ft/sec	7400 ft/sec	□ 15 ft East

Fig. 102. Normalized seismic amplitude vs depth (for all geophones).

- (4) There is constructive and destructive interference of the main energy arrival with refractions and reflections from nearby fractures and interfaces.

A number of runs on the one-dimensional program (SOC) were made to check (1), (2), and (3). Figure 103 gives the p - μ curves* and Fig. 104 gives the K - p curves used for the intervals labeled as materials 53, 52, and 51 on Fig. 102. Note that material 52 has been given a much lower shear strength than the other two. Runs were made in each material with a radius, r , of dry sand between the explosive and the material, and with $r = 0$. The value for r was chosen to be one-half the average caliber of the hole over the depth interval of the material being run. Values of peak particle velocity at a radius of 10 m from the shot point were taken from each run and are superimposed on the up-hole survey data in Fig. 105. Considered as a first attempt, agreement is excellent. One would expect some amplitude variation from constructive or destructive interference of the main wave with a reflected or refracted wave. However, such effects would not likely appear in the first peak except over depth intervals of $TV/2$, where V is the velocity of propagation, and T is the time interval between first arrival and first maximum (about 8 msec).

Between 200 and 150 ft, the data from the geophones begin to diverge, and above 150 ft they oscillate wildly. This leads one to surmise that the upper 150 ft is composed of highly disturbed rock. This is

* p is mean stress (pressure); $\mu = (V_0/V) - 1$, where V_0 is initial specific volume and V is specific volume at p ; K = deviatoric (shear) stress causing failure.

consistent with known fractures in the formation and with a hypothesis advanced to explain differing travel times from shot point to the three detectors.

We conclude that received seismic amplitude is related to lithology with regard to shear strength and/or water content. An effect due to reflection and refraction at nearby interfaces is also evident.

Since use of explosives is rather inconvenient in many cases, and an uphole survey also probably introduces perturbations due to intervening layers, the concept of a logging tool that uses a projectile striking a borehole wall seemed more promising. Propulsion of the projectile can be arranged later. A sidewall sampler serves as a model.

With this concept in mind, SOC problems were run. The SOC model of a projectile striking a wall is a spherical shell expanding with a given velocity and striking another spherical shell from the inside. The projectile material was chosen to be iron, and two different target materials, Schooner tuff (designated 4) and Sturtevant quartzite (designated 7) were chosen. The P - V curves of the target materials are shown in Fig. 106; they are very different.

Projectile velocities of 100 fps (corresponding to a sidewall sampler) and 1000 fps (corresponding to a shotgun slug) were used. The significant variable was the K - P curve. In all cases, a K of 10 bars was used for negative pressures. Then problems with K of 10, 100, and 1000 bars for all positive pressures were run for the 100 fps case, and 10 and 1000 bars for 1000 fps.

In the 100 fps case, particle velocities (which can be measured with geophones)

Fig. 103. Pressure vs μ for test problems.

Fig. 104. Shear strength vs confining pressure for test problems.

at 30 m from the contact point seem to depend only on K , not on P - V , except that in material 4 one cannot distinguish between a K of 100 bars and one of 1000 bars. This is attributed to the fact that, in that material, there is no crushing at either value of K , whereas in material 7 some crushing occurs at a K of 100 bars.

Figure 107 shows the results. The first digit of the problem number shown on the figure is the material number, the second, the negative power of 10 of K , in Mb (e.g., 74 is material 7 with a K of 10^{-4} Mb or 100 bars).

In the 1000 fps case (Fig. 108) things are not as good. The velocity seems to depend much more on P - μ , although in material 4, where two curves are shown in problem 45 (the first arrival and the crushed wave), there is a clear distinction between K 's. The material 7 problems show a similar difference, but it is not clear enough to plot on a graph; the waves are not well separated in problem 75.

It can also be seen from the figures that these differences are functions of the distance from impact, and this can be useful. It may be that by varying both

54	53	52	51	50	Material
<1%	5%	20%	3%		Water content
2.4	1.5	1.7	2.2	1.7	Density
7000 ft/sec	4000 ft/sec	6500 ft/sec	8800 ft/sec		o 15 ft West
7000 ft/sec	4300 ft/sec	6700 ft/sec			Δ 15 ft North
7000 ft/sec	4200 ft/sec	5500 ft/sec	7400 ft/sec		□ 15 ft East

Fig. 105. Amplitude-vs-depth curves compared to test-problem results.
(Horizontal lines show calculated values.)

Fig. 106. Pressure vs volume curves for the projectile problem.

impact velocity and distance, information about K-P and P- μ could be obtained.

SOC, of course, calculates velocity radially outward resulting from a radially outward impacting spherical shell, and is thus most unrealistic. TENSOR could be used, with modifications, to calculate the real case of velocity perpendicular to that of an impacting slug, but it appears both difficult and expensive. In any case, experiments would be required.

The next step, therefore, will be to experiment. The plan is to use a shotgun

to fire steel slugs at various velocities up against rock faces at Site 300 and at NTS. We suspect that we shall need larger velocities and shorter distances than those in the calculation to get useful results. But only trial and error will give us a technique.

The worst problem with the experiments is that we don't have large blocks of material with known K-P. This relation will have to be measured on samples of the materials we try, but of course the defects in laboratory measurements still remain. However, final surface tests should be in

Fig. 107. Projectile problem results (100 fps).

Fig. 108. Projectile problem results (1000 fps).

outcrops of material at NTS that have been run on SOC and TENSOR, and this can

give fairly definitive answers as to the feasibility of the method.

Cement Quality Logging

Emplacement holes, and even satellite holes, are often cased. The casing is held in place by cement, and there is often a question as to the continuity of this cement. Acoustic logs are often used to test the quality of the bond of the cement to the casing but this bond quality is not too relevant to nuclear explosive work.⁶² A more serious worry is the possibility of channels in the cement, through which gases from the explosion could vent.

At our request, the Nevada Test Site contractor developed a system for testing the quality of the cement and looking for such channels. This system consists of three standard diffusion density sondes mounted on a tripod arrangement so that they will contact the wall of a large hole at positions 120° apart. They are shielded from each other by lead, and tests have been made to ensure that one sonde does not see gammas from the others. Three traces are displayed at the surface.

The sondes are calibrated on a special trailer through the thickness of casing anticipated in the hole, and cement, CCl_4 , and air are used for calibration materials (although sometimes other liquids are also used).

The accuracy of this method is limited by the tolerance of the casing thickness, which is usually on the order of 0.10 in. but which, being steel, with density around 8 g/cm^3 , has the effect of much more cement. Errors on the order of 10% are caused by this perturbation. Another source of error is ignorance of cement

thickness. The casing is not necessarily centered, and if it is so close to the wall of the hole that the density readings are affected by the medium itself, further errors will arise. This is a problem mainly in small holes. Attempts have been made to develop an analytical technique to correct for this effect, but they have required so many unwarranted assumptions that they have not worked.

A multireceiver density sonde would probably solve the difficulties of casing variation and medium effect, but it has not been tried as yet.

In the Gasbuggy experiment, a refinement of the technique was used. A triple sonde instrument was combined with a Sperry-Sun directional survey sonde (see the following section). We know that generally cement-bond sondes rotate slowly as they come up the hole, and in the Gasbuggy case this rotation was monitored by the directional sonde, and thus traces of cement density vs both depth and azimuth were obtained. Several such traces were superimposed to obtain a picture of the entire hole. Special calibration fixtures were made for this survey using sections of hole casing.

Another difficulty is that in very large holes, the cement is too thick to be observed in its entirety by the density sonde. No plausible solution of this problem has been proposed. One method that might work, and that is being tried, is the provision of tubes outside the casing and the use of a fluid density log in these tubes before the cement sets.

Directional Surveys

It is common practice to use the Sperry-Sun directional survey apparatus to find the position of the bottom of a hole with respect to the top (and, the position of various points in the hole). The device measures angle of inclination and azimuth by photographing a pendulum type device and a compass in the hole. Then it is assumed, for normal data reduction, that the hole follows straight lines between measured points, at angles as measured at the bottom of the section (usually about 20 ft long).

A recent paper points out that results can be improved by assuming that the hole follows a circular path, with radii of curvature in the vertical and horizontal planes computed from the angles at both ends of the section.⁶³ Even with this improved method of data reduction,

however, considerable ambiguity exists, since more than one path can be followed between two sets of angles, and the method arbitrarily assumes the path to be the smallest arc of a circle in each plane. This ambiguity can be effectively removed by making the interval between measurements very small, but we have not done this to date.

A code, GORBAG III, has been written that computes positions in space of many points in each of two holes by either the standard method or the radius-of-curvature method, and then, by the Pythagorean theorem, computes range between these various sets of points. These ranges can then be used for hole-to-hole seismic surveys and for arrival time vs distance data reduction.

Radioactivity Logging

GAMMA-RAY LOGGING

Gross gamma count is a standard commercial log. In addition, the Nevada Test Site contractor has developed a high-intensity gamma log for use in post-shot holes. On one occasion, we have used the RIDS (density log) as a down-hole gamma spectrometer. While its resolution is poor (since the crystal is CsI and shielded by 2 cm of lead, a recognizable spectrum was obtained, and nuclides (⁴⁰K and the natural thorium chain) were identified.

We have proposed that a NaI crystal be canned and attached to the RIDS electronics

for borehole gamma spectroscopy, but so far there has been no demand for it. The use of solid state detectors with liquid nitrogen cooling would be more difficult.

HIGH-LEVEL RADIOACTIVITY MEASUREMENT

As early as 1962, geophysics personnel at LRL-Nevada were fielding a probe to measure radioactivity in the vicinity of a shot point. This unit consisted of a 1-in.³ ionization chamber with a built-in electrometer tube (Raytheon CK5886). The configuration is termed the "Neher-White Ionization Chamber." An operational circuit is shown in Fig. 109. The plate

Fig. 109. Ionization-chamber circuit.

Fig. 110. Plate current vs filament current for the 1-in.³ ionization chamber.

Fig. 111. Radioactivity log for Shoal.

current in a tube varies in a somewhat linear fashion with the logarithm of the radiation intensity in roentgens. The plate current also varies with filament current as shown by Fig. 110. The device is not particularly accurate, and it must be thoroughly calibrated before and after each use, but it has the virtue of a dynamic range as high as 6 decades.

The electrometer tube suffers irreversible damage if exposed to temperatures greater than about 40°C, but the complete chamber can withstand much higher temperatures for short periods. In downhole use, the unit was placed in a 1-1/2 or

Fig. 112. Radioactivity log for Salmon.

5-in.-diam tube packed with thermal insulation material such as Fibro-frax Alundum, or glass wool.

Figures 111 and 112 are parts of radioactivity logs from projects Shoal and Dribble. It can be seen that a wide dynamic range is required for these measurements. The very high peak at 2771.5 ft on Fig. 112 is the bottom edge of the Salmon cavity, which is overlain by approximately 23 ft of melt. Figure 112 shows the before-and-after calibration for Fig. 112. Total drift during logging was a factor of 2 in this case, but it was often worse elsewhere.

Fig. 113. Calibration curves for the Salmon log.

High-Temperature Logging

Temperature measurements of about 900°C in a highly corrosive atmosphere were planned for the Salmon Event. At the time, the available equipment consisted of a small winch truck with 5960 ft of 3/16-in.-diameter armored logging cable. The cable consisted of three conductors of No. 24 silvered copper wire; and one No. 24 chromel-alumel thermocouple lead wire pair, with FEP teflon insulation for exposures to 200°C.

Since the really extreme temperatures in a postshot environment are localized near the point of detonation, it sufficed to purchase three special high-temperature thermocouple cables 300 ft in length. These cables consisted of 1/8 or 1/16-in.-o.d. monel tubing, with the chromel-

alumel pair supported inside by tightly packed MgO. Of course, low temperature solders or brazing could not be used for fastening parts together. A cage was put around the junction to prevent damage, and sufficient weight was added to straighten the tubing since it was too stiff to extend itself under its own weight. At the top end of the tubing, a fixture was installed to connect to the cable head of our lower-temperature cable. The maximum diameter of the entire string was 1-1/2 in. Figure 114 shows the temperature log taken on the Salmon reentry. The maximum temperature of 400°F is lower than originally expected, since the reentry program was delayed approximately six months.

Fig. 114. Postshot temperature log for Salmon.

A complete report of the Salmon post-shot environment has been published.⁶⁴

Figure 115 is a postshot temperature log from the Shoal experiment, detonated in granite. In this case, the cavity had collapsed, forming a chimney approximately 27 m in radius and 110 m high.⁶⁵ The peak temperature recorded is 1120°F. The logging speed is approximately 2 fpm to reduce lag due to the time constant of the probe (about 20 sec in air). Approximately 30 min thus elapsed between recording the peak and plunging into 80°F water some 60 ft below the peak. This peak of 1120°F is the highest we have encountered in the field, although the probe has been calibrated in an oven at 1600°F and is expected to work properly as high as 2000°F.

This system has proved to be highly reliable and is recommended wherever high temperatures must be measured with an accuracy of a few degrees Fahrenheit. The major disadvantage is the long length of expensive thermocouple wire required. This is a serious

problem when the downhole cable must also serve other functions because the number of conductors available in the cable is limited. For these other functions, the chromel-alumel pair cannot normally be used as conductors because of their high resistance. For example, in the cable described above, the copper and chromel conductors had a resistance of 159 and 2350 Ω , respectively.

In order to solve this problem, we requested Consolidated Ohmic Devices to develop a remote thermocouple reference junction that would operate in an ambient temperature range of -56 to +315°C. The result was model JR347A1, which, when supplied with a suitable operating voltage, synthesizes a 0°C reference for a chromel-alumel thermocouple and allows the use of copper wires between it and the recording device. The intent is to use this device at the lower end of a logging cable for high-temperature logging, thus eliminating 7000 ft of expensive thermocouple wire from the cable. Birdwell or any other

Fig. 115. Postshot temperature log for Shoal.

Fig. 116. Test-run data from a downhole reference junction.

logging company could easily use this device on their cable, which means that a commercial source for high-temperature surveys can now be established.

Figure 116 gives the results of a test run on a unit. It can be seen that this junction compensates for an ambient temperature between 0 and 200°C with an accuracy of $\pm 0.2^\circ\text{C}$ when a supply voltage of 1.36 V is used. The compensation is

somewhat worse ($\pm 1^\circ\text{C}$) when a mercury cell (1.35 V) is used as the supply, but it is still usable. The device exhibits a load of about 6 k Ω to the supply, so power requirements are low, allowing long battery life and no power problems through long logging cables.

As a result of this development, we have eliminated the thermocouple wires from our new cable, which contains a 50- Ω coaxial cable.

Fielding

The downhole cable is carried on a large winch truck. Until recently, a discarded downhole television cable was used, but now the truck carries a 1200-m-long, 1.9-cm-diam double-armored logging cable, containing one coaxial (50 Ω) cable, two shielded No. 20 triplexes, three No. 16 wires, and six No. 22 wires, for a total of 16 conductors, not counting shields. The cable is supposedly good to 250°F. Before either of these cables was used, a small-diameter, seven-conductor armored cable containing a chromel-alumel pair was used, but it was unsuitable for the RIDS. However, until very recently it could be carried on a small drum on the back of the winch truck for use as a firing cable for uphole surveys.

Depth is measured by means of a selsyn attached to one of the sheave wheels. A similar method was used with the television cable, but since the cable was rubber-covered, the accuracy was poor. As of this writing, the selsyn has not been fully calibrated for the new, large cable, but repeatability appears very good. There is some controversy

as to the accuracy of the selsyn method, some loggers preferring magnetic markers on the cable. The controversy centers on problems of wear on the sheave (no problem with the markers) vs stretch on the cable (corrected with a table when using markers). Since we don't have facilities to prepare stretch tables and we don't use the system often enough to produce great wear on the sheave, the selsyn method is used.

A portable A-frame has recently been constructed to accommodate the large sheave wheels needed for the new cable and to carry the calibration blocks for the RIDS. One piece of information needed for good clamping in a hole, among other things, is the weight on the cable. In the past this was obtained by hanging the upper sheave on a load cell; with the new A-frame there is strain-gage instrumentation on the sheave shaft to indicate weight on the cable.

Most of the recording equipment for our logging systems is carried in a van, consisting of a superannuated military 6x6 truck with an air-conditioned box

Fig. 117. Field equipment for geophysics research.

and a generator mounted on it. The van also carries a large battery pack for silent operation during uphole surveys and various communication equipment. The sondes and (until very recently) the

RIDS calibration blocks are handled by a small crane mounted on a pickup truck, which also serves to tow the A-frame and carry extra gear. The rolling stock is shown in Fig. 117.

Data Processing

PROBLEMS AND POTENTIALS

A processing system is being specified to enable physicists and geologists to obtain physical parameters and stratigraphic description from geophysical logs. The need for this system arises because the physicist needs the best available set of physical parameters for his code runs, often within a short time from acquiring the original logging data in the field. A large quantity of logging data is recorded on cumbersome strip charts in units that are convenient for the electrical analog recorder. The geophysicist must then provide physical parameter information through various data reduction programs. These programs, in turn, should be brought up to date continually as more understanding of the corrections develops. This implies that the geophysicist must return to a file of raw or undisturbed data representing the actual trace on the log before reprocessing through new sub-routines to a file of computed parameters. The geologist requires a convenient collection of corrected data on library tapes and on machine plots so that there is a minimal amount of paper work required for geologic and stratigraphic description. Further, there can be statistical, topographical, and other special-purpose programs requiring a composite tape of

physical parameters compiled at a common depth under various criteria specified by the user. A more complete and enthusiastic discussion of geophysical data processing is given in a paper written by B. M. McVicar in the April 1968, issue of World Oil. It is entitled, "Log Analysts Can Use Seismologists' and Gravity Interpreters' Methods to Great Advantage." McVicar's article illustrates that a statistical approach to log analysis may yield lithology, error correction factors, input for contour plots, data noise reduction, credibility limits of a log, and perhaps, physical parameters that are now difficult to obtain.

Recognizing the inherent problems and potentials of this process, it is the purpose of this data-reduction system to provide a broad base of information input for future programs and to calculate routinely the more commonly used parameters in a standard library available to anyone.

The data-reduction system, as envisioned from the existing situation, must contain certain basic elements: a library of current, undisturbed data, which will be referred to as the Master Raw Data Tape Library, and a second library of current computed parameter data, which will be referred to as the Computed Parameter Tape Library. This system

must have the capability of collecting data from different sources and condensing them for each library. It should be capable of running production data efficiently, but it should still allow for continuing changes in the programming and processing of problem logs. The system should have the versatility to combine any number of parameters under one depth. A general system of this type poses other problems that require further programs; for instance, a maintenance program is required to indicate completeness of the input data, to keep a catalog of the various library tapes, and to give some indication of how computed parameters were calculated.

The major problem which besets a program of this size is definition. If all future requirements for this data-retrieval system were known, then programming and problem definition would become more specifically organized. Programs written in a general way are required in the initial phase. This sacrifices programming time, core storage, and computer time, but it results in greater adaptability to all types of data. To convey general concepts about a broad range and large quantity of data often causes considerable confusion to programmers who are not versed in the field of geophysical logging. Again, many subtle unknowns and data problems are not foreseen by those of us who define the problems. These problems could be solved by a good programming geophysicist working on a full-time basis.

A secondary problem that besets a system of this size is that of quick returns. It is often the case that tangible results must be seen within a shorter

time frame than is estimated to complete the work. We have attempted to provide parallel systems to alleviate this problem. The use of the parallel system requires additional programming cost, but it may provide useful information for defining nebulous ideas.

Two parallel systems are in operation at this time. One system has been developed at LRL-Nevada, and a second system is incorporated in the EG&G program system.

SYSTEM I (LRL-NEVADA)

The LRL-Nevada system was set up to digitize, calculate parameters, and replot at useful scales. The block diagram of this system is shown in Fig. 118.

The digitizer is a more recent model of the RAND tablet.⁶⁶ Field logs are placed on the digitizing table, which generates specific pulse trains for each discrete X,Y location on the board. An electronic pen acts as an antenna to pick up a specific pulse train, which is dependent on its location over the board. This enables paper to be placed between the board and the pen. The distance between each digital point in the X or Y direction is 0.01 in. where the total tablet measures 10.24 by 10.24 in. The tablet may be run in a single point or continuous mode, depending on whether one point or the full digitizing rate of data, is desired. The maximum data rate, which is limited by the paper punch output, is approximately 7 data points/sec. The digitizer is built so that a difference between the last digitized point and a new point must be detected before an output is generated. This ensures that the same

Fig. 118. Block diagram of the NTS data-reduction system.

point will not be digitized twice. Data are output as 20 bits/data point and distributed into the first three binary levels of a BCD-image, 7-level paper tape. This is not a standard output.

The Grafacon system also contains a keyboard to enable manual entries to be made on the paper tape. Because of the peculiar bit configuration of the data entries, keyboard entries are easily discriminated from data and may be used by the operator to signal a variety of program instructions to be performed on the data. The paper tape is then mounted on an IBM Model 1620, which also drives a card punch, a paper tape punch, and a Calcomp plotter. The paper tape punch has been modified to accept and process large rolls of paper tape, so that logs may be processed unattended during the night.

The first-generation computing equipment used in the processing of logs is quite slow, but it is somewhat compensated for in the ease of using the system and the features of night processing.

The software programs are divided into three parts.

Part 1

This part converts the digital units of the RAND tablets to the units read on the original log. This program has the following general features:

- (a) It converts binary to BCD.
- (b) It orients the axis of the digitizer to the X-axis and Y-axis of the log through a dot product.
- (c) It reads in the actual values from the paper tape of three axis points on the log, and converts them to an X and Y scale of units/in.
- (d) It contains the options of reading off of semi-log or log-log graphs and converting the digital units accordingly.
- (e) It contains the option of entering up to 20 calibration points for a nonlinear scale that is superimposed over the digital three-point scale.
- (f) It performs an automatic continuation function that puts frames of long strip charts together at the proper point and recalculates each frame. For example, the operator divides his log up into frames of less than 10 in. The borders of the first frame are completely defined by three digitized points, and by actual log units. In the example of Fig. 119, a frame is set up for a depth of 150 ft. The operator digitizes the three points marked with X's and enters their true values from the keyboard. Then he proceeds to trace the data curve until the point limit or 150-ft line is reached (Point A to B). A keyboard entry is made to indicate a continuation, and then the strip chart is moved to the next frame and three points (shown as 0's) are touched with the pen. The actual values of units/in. are applied to this frame, as well as any reorientation of log to digitizer. This method insures a reasonably fast digitizing rate for the operator and a tight control over scale changes due to shrinkage of the strip chart paper.
- (g) The program can be keyed from the Grafacon to incorporate scale shifts in the data. These are

Fig. 119. Sketch of a sample Grafacon frame.

typically seen in the temperature log and in Schlumberger density logs.

- (h) The program can be keyed from the Grafacon to incorporate times 10 scale changes in the electric log.
- (i) The program can be keyed from the Grafacon for processing two log traces at each frame. Each trace is input with separate scales, and each curve is stored at common depth point.
- (j) The fast response of some curves can be changed to match other slow response curves (see the section on time constants).
- (k) Each log trace may be integrated with depth and differentiated with depth for an output listing.
- (l) The output of each log may be pre-selected from the Grafacon keyboard. Output options are shown in Table 7.

Part 2

This software program contains the computational conversions for each log. This program is necessary to incorporate corrections, conversions, and additional information required for a specific log.

The input format to this program is in one of the paper tape output formats from the first program. The first word that is read on tape before each log defines the data format, the log type, and any constant that should be used to correct the log. Logs may be read sequentially from one large roll of paper tape with varying formats for each log.

The output of this program is on cards, or paper tape, in one standard format [8(E 12.6, 1X)]. The number of columns (or fields) used is dependent on the data required for each log. These columns increase in number from left to right across the card. The standardized format is used for the generalized plot program that can plot any column against any other column.

The following are log types and their respective conversions, and list of outputs.

Density Log with Kilocount Proximity Input Traces

The output for this log is shown in Table 8. A complete explanation of the conversions is found under the density log. The proximity trace is smoothed digitally to match the response of the kilocount curve (see the section on time constants). The kilocounts are converted to raw density units from two calibration points by

Table 7. System 1, part 1, output options.

	Depth	Y	INT.	Depth 2-pt av	Y 2-pt av	$\frac{dY}{d \text{ depth}}$	Format
CARD OUTPUTS							
Number of data points per card	3	3	3				3(E12.6, 1X)
	1	1	1	1	1	1	6(F8.6, 1X)
	5	5					5F8.2, 5F8.4
	5	5					10F8.2
	Depth	Y ₁	Y ₂	Integration	80 Char		Format
PAPER TAPE OUTPUTS							
Number of data points per card	4	4	4				4(F8.2, 2F6.3)
	2	2	2				6(E12.6)
	5	5					5F8.2, 5F8.4
image	5	5					10F8.2

Table 8. System 1, part 2, output for the density log with kilocount proximity input traces.

Column					
1	2	3	4	5	6
Depth (ft)	Proximity (in.)	Raw density (g/cm ³)	Corrected density (g/cm ³)	Integration (0.6 in. proximity cutoff)	Correlation
Dep	Prox	Px	Pc	Int	Cor

$$\rho_x = \frac{\ln \frac{K_{cntX}}{K_{cnt1}}}{\ln \frac{K_{cnt2}}{K_{cnt1}}} (\rho_2 - \rho_1) + \rho_1$$

where

ρ_x = raw density from data curve,

K_{cntX} = count rate from data curve,

ρ_1 = density of calibration 1,

K_{cnt1} = count rate of calibration 1,

ρ_2 = density of calibration 2,

K_{cnt2} = count rate of calibration 2.

The corrected density is adjusted from the raw density for the gap between the tool and the hole wall by

$$\rho_c = [(K_1 (b_B/3) + (b_B/3 + 1)) (\rho_x - K_2) + K_3$$

where

K_1, K_2, K_3 = constants,

b_B = proximity.

The integration is calculated by the standard trapezoidal form

$$Int = \sum_{i=1}^N \frac{\rho_c(i) + \rho_c(i-1)}{2}$$

$$\times [Dep(i) - Dep(i-1)].$$

Since gap calculation is considered in error above 0.6 in. gap, or 0.2 in. at the point of density measurement,⁶⁷ the integration holds the value of the five previous

averaged density points until the proximity measurement returns to less than 0.6 in. This technique is used to restrict the influence of erroneous density corrections on the total integration value.

The correlation with a step function can be a'ided by request of the user (see the section on correlation).

The Resistivity Log Data

The data are output in two sets of printouts. The first set is for the spontaneous potential and 16 in. normal traces, and the second set is for the 64 in. and 18 ft 8 in. lateral traces (see Table 9). No corrections are performed on this data.

The integrations for each curve are the standard trapezoidal form.

The 3-D Log

For P-wave, or shear-wave traces, the 3-D log data are reduced with the two-tool method. Data from one tool length is input on either tape or cards and

stored. The second tool length data is input and correlated to give the output shown in Table 10. The integration is the standard trapezoidal form. If average velocities are to be calculated, the total travel time column should be used in place of the integration.

Average Velocity

$$= \frac{\text{Dep } 2 - \text{Dep } 1}{\text{Total time } 2 - \text{Total time } 1}$$

The total travel time column is calculated by

$$\text{Total time} = \sum_{i=1}^n \frac{\text{Dep}(i+1) - \text{Dep}(i)}{\frac{V(i+1) + V(i)}{2}}$$

The Continuous Velocity Log

This program converts the input data, which is in $\mu\text{sec}/\text{ft}$ to velocity units.

$$\text{Ft/sec} = \frac{1 \times 10^6}{\mu\text{sec}/\text{ft}}$$

The data are then output with integration and total travel time in the same format as the 3-D log.

Table 9. Resistivity log data outputs.

Column					
1	2	3	4	5	6
Depth	$(\Omega - m)/m^2$ (16 in.)	Integrated 16 in.	Spontaneous potential (11 in.)	Integrated spontaneous poten- tial	
Depth	$(\Omega - m)/m^2$ (18 ft)	Integrated 18 ft	$(\Omega - m)/m^2$ (64 in.)	Integrated (64 in.)	

Table 10. 3-D log data output.

Column					
1	2	3	4	5	6
Depth	Velocity km/sec	Integration km.sec	Velocity ft sec	Velocity m/sec	Total travel time

The Gamma-Neutron Log

This log is output in the same units as the original log (see Table 11). The integrations are the standard trapezoidal calculation.

A Double Trace from Any Other Log

A double trace may be run through this program and the output shown in Table 12 will be obtained.

An Output for Any Single Trace Log

This program will produce the output shown in Table 13.

The SEISCOMP Program Inputs

Seismic data from uphole or downhole shots can be input by cards that give the

vertical distance and the time of arrival to the geophones. This program adjusts the time data to originate from the surface and corrects the time data to the vertical distance in the hole rather than the true hypotenuse distance. The data is output in card form and is formatted for use in reports. The corrected time-depth data in the output is formatted (4X, F5.0, 38X, F6.4).

The 3-D velocity program and the Seiscomp program are separate from the multi-log conversion program because of core storage limitations in the IBM 1620 computer. All three programs prepare the data for the plotting routines.

Table 11. Gamma-neutron log data output.

Column					
1	2	3	4	5	6
Depth (ft)	Neutron trace calibra- tion units	Integration (neutron)	Gamma API units	Integration gamma	Blank

Table 12. System I, part 2, double trace data output.

Column					
1	2	3	4	5	6
Depth (ft)	Trace 1 (units of log traces)	Integration (trace 1)	Trace 2 (units of log traces)	Integration (trace 2)	Blank

Table 13. Single trace log data output.

Column					
1	2	3	4	5	6
Depth (ft)	Trace (units of log trace)	Integration	Blank	Blank	Blank

Part 3

The third part of the software program consists of the plot routines, which contain three separate programs.

Density Plot Program

The density plot program will accept cards or paper tape. It outputs the smoothed proximity, the density uncorrected for proximity, the corrected density, and the correlation curve (if requested). The standard plot is shown in Fig. 19. The depth scale (in ft/in.) must be selected prior to running. The data input format is 6(E12.6, 1X).

Multi-Log Plot Program

The multi-log plot program accepts cards or paper tape in the same format as the density log: 6(E12.6, 1X). This program was written with the option of plotting any of the 6 columns vs any other column. The scales of the X and Y axis must be preselected prior to running. This program offers the option of one to three strip chart scale graphs on a 10-in. wide graph, as well as any number of overplots at each scale. At least five colors may be requested, as well as two different character sets to differentiate the curves. The program is versatile enough to give linear plots of any data that is run through the Grafacon.

Seismic, 3-D, and CVL Plot Program

This program is a special program to accept total time vs depth from seismic, 3-D, and continuous-velocity logs and plot them at various scales. The plots of the total travel time vs depth facilitates the picking of velocity breaks in the data.

Practical Considerations of the Nevada System

The Nevada data system is quite versatile for processing of logs for special projects and events. Its main limitation is the core storage and the speed of the hardware. There is a considerable amount of operator time spent from digitizing to completion of the logs. For this reason, the Nevada facility is not used to digitize all the logs on a day-to-day basis. The turn-around time between request in Livermore and return of computed material may vary between 3 to 10 working days, depending on the amount of data requested, the importance of the data, and the hardware that is working.

It is suggested that logs containing special calibration or scale changes should be discussed with the operator before the data are processed.

SYSTEM II (CONTRACTOR)

Parallel system II is presently used with logging data digitized and computed by Birdwell. This EG&G system is divided into three programs. The first program (lib in Fig. 120) is called the Birdwell composited tape conversion (BCTC) program. It converts Birdwell computed parameter tapes containing the following information: heading information containing hole name, north-south coordinates, east-west coordinates that assume that the state coordinate system is used, and elevation from sea-level of the zero depth of the log. Also included in the heading are the total depth of the hole and the run numbers for each log type. The only log types that have been

(II b)

(III)

(IV)

(V)

* These programs are not defined at present.

Note: All tape outputs in phases II, III, IV, etc. will be in the working data tape format (WDT).
The output WDT from any program may be processed by the print/plot utility program.

Fig. 120. Block diagram of additions to the EG&G system.

digitized to date are the 3-D, density, caliper, gamma-neutron, electric and temperature. The computed parameters on the tape are depth, P-wave velocities, S-wave velocities, sonic density of debatable validity density from gamma-gamma corrected for gap, porosity, water saturation, bulk modulus, shear modulus, Young's modulus, Poisson's ratio, compressional wave weighting factor, shear wave weighting factor, and density weighting factor. The methods of calculation and the validity of the various moduli are discussed in a memo by R. Carlson.

This EG&G program converts Birdwell computed data into an intermediate magnetic tape with standard format. The standard format will be used between programs in the final EG&G system and will be referred to hereafter as a working data tape.

A second program (III in Fig. 120) called Extract and Merge Program receives any working data tape for any hole and organizes all parameters according to depth or elevation. (Very often elevations of the hole have been left off the tape.) This puts the data in a form so that complex manipulation between logs may take place with relative ease.

A third program (V in Fig. 120) is the Working Data Tape List and/or Plot Program. This program produces listings and plots of a specified parameter and hole location. Parameters are retrieved from magnetic tape and plotted against depth. This program will read outputs from programs IIb and III. The program will set up its own scaling, if not specified by the user. The Calcomp plotting output is essentially the same as the plotter output specified under the

general LRL-Nevada plot program. It is capable of one to three plots on a 10-in. graph on the Calcomp. This program is somewhat limited in that depth must be on one axis vs any data parameter. The data must be merged with program III before any overplots can take place. The plot program is restricted to two overplots.

Practical Considerations Regarding the EG&G System

It should be pointed out that only the log types and parameters mentioned in the BCTC program are available at this time. Program IIb is the only part that will be phased out when the full EG&G system is working. Programs III and V will be used (with some modification) in the final system.

The LRL Geophysics EG&G Data Processing System

The system outline shown in Figs. 120 and 121 has been subdivided into programming blocks. Program Ib is a reception center for all types of available log data and their respective headings and calibrations. At present, the system is specifically designed for inputs from the Birdwell digitizer and the LRL-Nevada Grafacon. The data from these sources are eventually converted to magnetic tape. Card inputs to Ib will also be provided for control and for input of logs not yet defined. The logs specified thus far for Ib are the caliper, density, 3-D electric, neutron, temperature, fluid density, the Nuclear Cement Analyzer, and any log trace of general form. Eventually, we expect to add more Birdwell log types to this list and also some LRL geophysical data and logs run

(Ia)

(Ib)

(Ic)

(II a)

Fig. 121. Block diagram of the EG&G data-processing system.

by other companies. The Birdwell logging data input was specified by separating the logs into individual traces with complete information of the log contained under each trace. Each trace, furthermore, contains heading data, before and after calibrations, calibration and scaling information for the

trace, and any further data tables that we suspect may correct the response of the tool. There will still be uncertainty as to the completeness of all the items listed under a trace until we understand better what affects the tools adversely. This uncertainty is manifested in the

definition of program I¹ for processing data. The presently accepted solution for this difficulty is to maintain generality in programming so that changes do not become major perturbations on the system.

The log data incorporated in program Ib is output on a master raw data tape under a hole name and by trace type. The purpose of Ib is to write all input data from different sources onto a small number of library tapes without changing the data in any other way. At the same time, the system will keep track of items that are omitted on the input logs so that some form of quality control may be maintained. Program Ib must also be able to generate an updated library in the first tape file of the master raw data tape. At the same time a catalog correction tape will be written with all the latest additions of logs made to the master raw data tape. Each log on the correction tape will contain a list of all items from the Birdwell or Grafacon tape that were left blank.

The catalog correction tape is used as an input to the catalog data processing program (Ic) which will keep an account of the data and the tapes throughout the whole system. This program must be able to keep track of two library tape systems: the master raw data tapes from Ib and the computed parameter tapes from III. To accomplish this, various listing options will be available at the user's request, and a standard listing of all data added or deleted from each of the two libraries will be made as a matter of course. The listing options available to the user at this point in the data reduction process are (1) a listing of logs that fall

within the input limits of given cartesian or cylindrical coordinates, (2) a complete listing of all logs on any or all area tapes, (3) a listing for any number of specified "omitted input items," (4) a list of the same trace types that overlap in depth in the same hole, (5) a list of traces as specified under any part or all of hole designation characters such as central Nevada, area, hole letters, hole type, and number of the hole, such as satellite hole #3. The above-mentioned listing programs should be useful for planning data reduction projects that fall into these categories. For production processing of new data. A set of processing control cards will be punched by program Ic for each listed log as an input to program I¹a, thereby avoiding the possibility that some of the incoming raw data might be overlooked for the data processing program.

The purpose of the master data processing program is to convert from the digital scales of the various digitizers to the scale of the log trace and then to further convert these log traces into useful parameters. An example would be to convert the digital units on the magnetic tape to the trace units of kilocounts and proximity and then convert them to corrected density, etc. Since the procedure for reducing these logs may change from time to time, it was decided that the programming should be broken down into basic building blocks or subroutines that may be called, and changed, at will. These subroutines must be able to perform a variety of functions such as scaling, calibration, tape search, reading specified parameters, detection of errors in the data, performing procedures for

calling other routines, calculating specific parameters, etc. Under normal production processing, each log type will have a procedure subroutine in this program which will call all the other subroutines to perform their functions in the proper sequence. This subroutine may be bypassed by calling the sequence with control cards or by adding or changing the subroutine internally and placing the date of the change in the procedure subroutine. The process for bypassing the procedural subroutine is as follows: The control card input will contain a hole designation and log type on the first card. The second card will contain a subroutine number with blank fields to the right of the number. The fields may be used in special cases to input data for that subroutine. This will allow editing of data from the raw data tape or the addition of special processing constants. The second card may be followed by any number of subroutine cards in the order that they are to process the data. Only two cards are necessary for normal production. For this case, the hole designation and log type card will be followed by only one procedure subroutine designation card. This card, of course, automatically calls the other subroutines in sequence internally.

In order that adequate editing may take place in program IIa, the following procedure should be followed. All data added to the master raw data tape should be processed through the procedure subroutines, as defined by the output cards from the Ic program. The output tape should then be plotted in such a way that the reviewing geophysicist can determine if errors are present and if the standard

data reduction technique is adequate. If the processing is not acceptable, the geophysicist must devise routines and procedures that will process the data to his satisfaction. When the geophysicist determines that his last run through the data processing program was acceptable, then the catalog correction data tape is saved for updating the parameter tape library through program Ic. As the processing subroutines are improved from time to time, it becomes increasingly difficult to reconstruct how some of the older computer parameters were calculated. To alleviate some of this problem, the catalog data tape for the computed parameters library will contain information on subroutines used in processing the data. This information will include the subroutine numbers, the data of the subroutines or date of processing, and the name of the geophysicist or log analyst responsible for reviewing the processing of the logs. An example might be the following list: parameter type, density, proximity; subroutine number, 02; date, 12/10/68; log analyst, Carlson. Or for a specially processed log it might be: parameter type, density; subroutine numbers, 7, 13, 18, $23 + 3.7 \times 10^8$, + 2.1416, + 375., 79; date, 1/12/69, log analyst, Carlson, and so on. This second example illustrates that constants used for special processing should be included on this list. The date in the first example is the date given in the density procedure subroutine, and the date in the second example is the processing date. (This difference is due to the fact that no procedural subroutine was used in the second example.) This date will be used in two listing options provided

in the catalog data processing and reporting program. One option is to list all the data processed prior to the currently used procedure subroutine dates. The other option is a listing of any processed parameters by subroutine numbers, dates, or by the name of the responsible log analyst. These listings of subroutine numbers must be correlated with a written description of the subroutines for a more detailed description of the data processing of a particular parameter. From the above listings, the geophysicist may then choose to reprocess much of the data again. The listing options used in the master raw data tape library will also be available for the parameter tape library. The catalog of parameter tapes will contain the Birdwell computed parameters from program 1b that are in current use in the parameter library.

For production work by EG&G, a set of control cards will be punched by the catalog data processing program for control of the extract and merge program (program III). This feature will insure that the library of parameter tapes contains data merged in the exact sequence that is given by the current catalog data tape.

The purpose of the extract and merge program is to bring all the useful geophysical parameters together at one depth. This is the program that makes the computed parameter library tapes. Since logging data are seldom recorded in the field or digitized completely at one time under one hole, it is necessary to process and merge the following data in the sequence that they arrive at EG&G. This procedure insures that a current library of computed parameters is maintained

and the data are available for immediate use. The merge program is not limited to data at common depth under one hole name. The user may merge any number of holes, parameters, or tapes in the complete library either by elevation depth or by log depth.

The geophysics data processing system contains the feature of making all the working data tapes from parts IIa, IIb, and III in an interchangeable format. This format may be used as input to the merge program (III) and to the utility print and plot program (see Fig. 121). This will enable the user to acquire data listings and plots from the IIa, IIb, and III programs. A geologist, for example, could easily request machine plots of all the computed parameters in one hole with depth as the common ordinate.

This, at present, is the extent of the planned geophysics data processing system. It is hoped that this system is general enough to gather the correct data in the right sequence for future processing and plotting programs.

DENSITY CORRELATION WITH A STEP FUNCTION

The correlation routine that has been incorporated in the density log is the first attempt at mathematical modeling. The method was borrowed from the Soviet literature⁶⁸ showing the applications of information theory to gamma-gamma density logging. Density data are cross-correlated with a step function.

Because of the statistical fluctuations seen in density logs, it is somewhat difficult to pick useful information, such as layering, from the heavy statistical interference. The type of information

it attempts to enhance is the layering in the medium. The idealized model for a layered interface is a step function of density.

The step function model that is used is somewhat arbitrary in its values of density, but the length of the model determines the amount of noise filtering with depths (see Fig. 122).

The length used was 16 ft per level. This length was selected on the basis of computer memory. More useful enhancement of data may occur by adjusting the length of the step. The expression used is:

$$\text{Cor} = \left([x_{\text{int}2} - x_{\text{int}1}]1.9 + [x_{\text{int}3} - x_{\text{int}2}]1.6 - [1.9(\text{Dep}2 - \text{Dep}1) + 1.6(\text{Dep}3 - \text{Dep}2)] \right) \times \frac{x_{\text{int}3} - x_{\text{int}1}}{(\text{Dep}3 - \text{Dep}2) + (\text{Dep}2 - \text{Dep}1)} \quad (47)$$

where

Cor = Correlation value,

Dep(1,2,3) = Depth values at points 1,2,3,

xint(1,2,3) = Integration values of the density trace at depths 1, 2, and 3.

The model is correlated with the data at each density point and indicates positive values for high-to-low density steps, negative values for low-to-high density steps, and zero for statistical independence.

Figures 123 and 124 show the correlation function indicated by (+) over-

plotted with the raw (uncorrected for gap) density curve.

The plots appear to be related to the tops and bottoms of wash-out zones in the caliper log. In this example, the peaks should aid the geologist in picking the depth of layered zones. In the cases where more subtle information is being sought, the use of a 70- to 100-ft model would seem more appropriate. This could enhance the picking of the tuff-alluvium interface, as well as the water table.

The method used here certainly could be applied to other logs to enhance information. Perhaps the most important use would be in the evaluation of various models for different types of geologic occurrences. For example, one model could be used in a search of the water table location as opposed to another kind for the alluvium-tuff interface, and so on.

Equation (47) is calculated from the general form [Eq. (48)], where the data points are assumed to be equally spaced.

The discrete form of the correlation function is

$$K_{\text{DIT}} = \sum_i^N D_k M_k - \bar{M} \sum_i^N D_k \quad (48)$$

where

D = Data point evaluated at point "K,"

Fig. 122. Illustration of the density step function.

Fig. 123. Sample step-function correlation with density.

M = Model points evaluated at point "K."

If the data points are equally spaced in depth, then this formula is easy to use. The digitizer used in Nevada does not use even increments of depth, so total integrations of the data curve from the surface to the points on the curve were used. Depth increment is used in place of N for average values.

$$\lim_{N \rightarrow \infty} \sum_{i=1}^N D_k M_k = (x_{int2} - x_{int1})1.9 \\ + (x_{int3} - x_{int2})1.6$$

$$\lim_{N \rightarrow \infty} \bar{M} = \frac{1.9(Dep2 - Dep1) + 1.6(Dep3 - Dep2)}{(Dep3 - Dep1)}$$

$$\lim_{N \rightarrow \infty} \sum_{i=1}^N D_k = x_{int3} - x_{int1}$$

Eq. (48) = Eq. (47).

Problems of starting the correlation at the very top of a log are encountered because the top of the model is cut off. The inverse problem is present at the bottom of the log. The solution used in this routine is to fictitiously extend the value of the top data point 16 ft above the top log point and 16 ft below the bottom log point.

The method appears to work well, but it has not gained acceptance or use by the geologists. More work should be done to incorporate models more acceptable to the geologist.

This subroutine is available in the standard density code, which is run at LRL-Nevada and is available only by request of the user.

Fig. 124. Sample step-function correlations.

Available Logging Systems

A list of logging systems available from various sources has been compiled as UCIR-401 (for internal distribution only).⁶⁹ No claim is made that the list

is complete, but it discusses systems of which the authors have some knowledge. It is suggested that the authors be consulted before planning a logging program.

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